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OPTIMIZATION OF HYBRID RENEWABLE ENERGY SYSTEMS ON ISOLATED MICROGRIDS: A SMART GRID APPROACH

Doutoramento em Sistemas Sustentáveis de Energia

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Abstract

The energy systems of small isolated communities face great challenges related to their autonomy and resilience, when looking for a sustainable energy future. Hybrid renewable energy systems, composed from different technologies, partially or totally renewable, potentiates a growing security of supply for these isolated micro-communities. Moreover, with a smart grid approach, the possibility to reschedule part of the electricity load is seen as a promising opportunity to delay further investments on the grid's power capacity, enabling a better grid management, through peak load control, but also to promote a more efficient use of endogenous resources, maximizing renewable penetration.

To identify the micro-communities main energy challenges, a literature review was taken, reporting the design and implementation of isolated hybrid renewable energy systems. Since electricity and heat energy vectors can be, in part, assured by endogenous resources, a methodology to optimize demand response on isolated hybrid renewable energy systems was developed, using the electric backup of solar thermal systems for domestic hot water supply as flexible loads. This approach is intended to increase energy efficiency of the energy system, reducing grid operation costs and associated CO_2 emissions.

A model of the electric impact of the implementation of solar thermal systems and heat pumps for domestic hot water supply was developed and tested for the Corvo Island case study, a small and isolated microgrid, located in the mid-Atlantic with around 400 inhabitants and a diesel power plant. An impact of 60% on peak load and 7% on annual electricity demand was found. In order to tackle this significant impact in the grid, a model for optimizing the economic dispatch of the island was developed, testing multiple demand response approaches to the backup loads, from heuristics to genetic algorithms, having this last one performed best to control the peak load and minimize the operation costs. Nonetheless, there was the need to compare and validate the demand response optimization strategies of this developed model with other available modeling tools, which in the end presented similar results.

As the pillar of this thesis is the optimization of hybrid renewable energy systems, the influence of the uncertainties associated to renewables forecast had to be studied, in particular its impact on the demand response scheduling. Wind uncertainties demonstrated to have a greater impact on the grid than the solar ones.

Finally, the methodology developed incrementally along the thesis and validated in Corvo Island, was tested on different scales and types of isolated systems. It demonstrated to be especially suitable for small systems with less than 20 MW power installed and over 25% renewable generation, with mostly residential load profiles.

Keywords

Demand response; Thermal storage; Smart grids; Isolated microgrids; Hybrid renewable energy systems

Resumo

As pequenas comunidades isoladas enfrentam grandes desafios relativamente à autonomia e à resiliência dos seus sistemas de energia. Os sistemas de energia híbridos e renováveis, compostos por várias tecnologias, renováveis parcialmente ou na totalidade, potenciam uma maior segurança de abastecimento e, consequentemente, uma maior sustentabilidade para estas micro-comunidades isoladas. Adicionalmente, a capacidade de, em sistemas isolados, mobilizar parte do consumo de electricidade para outras horas do dia, apresenta-se como uma oportunidade promissora: tanto para a optimização da operação da rede destes sistemas, levando a uma regulação do pico de consumo; mas também produzindo poupança económica para o utilizador final, se este usufruir de tarifas diferenciais. Deste modo, a necessidade de novos investimentos em capacidade do sistema energético é adiada, como também se contribui para o uso mais eficiente dos recursos renováveis endógenos, e, no caso de sistemas com consumo de combustíveis fósseis, a uma redução das emissões de gases com efeito de estufa.

Tendo em conta que os vectores da electricidade e do calor podem ser assegurados em parte por fontes renováveis endógenas, foi desenvolvida uma metodologia de optimização do despacho de cargas flexíveis em sistemas isolados, usando para tal a capacidade de armazenamento térmico dos tanques de água quente dos sistemas solares térmicos. Com esta metodologia, quis-se aumentar a eficiência energética total do sistema energético, reduzir os custos de operação da rede e as emissões de CO_2 associadas.

Tendo começado por caracterizar as micro-comunidades isoladas em termos de configuração e implementação de sistemas energéticos híbridos e renováveis, foi identificado que os sistemas híbridos mais utilizados em ilhas são centrais térmicas a diesel, integrados com energia eólica e fotovoltaica, enquanto que nas comunidades remotas, tipicamente mais pequenas e com menos infraestruturas, são compostos por energia solar fotovoltaica, apoiada por geradores unitários a diesel e complementada pelo uso de baterias.

Os sistemas de armazenamento para sistemas isolados de energia de maior escala, como é o caso das ilhas estudadas, ainda apresentam desafios técnicos. A inexistência ou inadequabilidade dos sistemas de armazenamento actuais limita, na maior parte dos casos, uma maior taxa de penetração de energia renovável, que tipicamente não ultrapassa 50% do total de produção de electricidade.

No que respeita ao abastecimento de calor, concluiu-se que este é assegurado na sua maioria por combustíveis fósseis, e na lógica da maximização do consumo de fontes endógenas, a introdução de sistemas renováveis neste vector é essencial.

Usando o caso de estudo da ilha do Corvo, nos Açores, que viu ser implementado para abastecimento doméstico de água quentes sanitárias (AQS), sistemas solares térmicos e bombas de calor, modelou-se o seu impacto eléctrico na rede, resultando num aumento de 7% na energia consumida anualmente e

em 60% do pico de consumo, o que para o sistema energético em questão seria incomportável. Para contornar um tal aumento, várias estratégias de optimização dos consumos eléctricos introduzidos pelo apoio dos sistemas de AQS, foram testadas. Considerando flexível o apoio eléctrico destes sistemas e tendo como objectivo optimizar o seu despacho, reduzindo os custos de operação da rede eléctrica, diferentes estratégias de optimização do consumo adaptativo foram modeladas, utilizando modelos heurísticos, programação linear e algoritmos genéticos, utilizando para isso várias formulações em termos de quantidade de energia flexível e em termos de número de sistemas AQS ligados/desligados.

A optimização das cargas flexíveis através dos algoritmos genéticos, obteve os melhores resultados de minimização dos custos de operação e energia consumida, obtendo uma redução de 1% para o caso de estudo do Corvo, quando comparado com um cenário de cargas fixas, ou seja, sem estratégias de consumo adaptativo.

No entanto, existindo outras ferramentas de simulação de sistemas híbridos e renováveis, com funcionalidades de modelação de consumos flexíveis e adaptativos, o modelo desenvolvido para o caso de estudo da Ilha do Corvo, foi comparado e validado com outros modelos existentes no mercado (HOMER e EnergyPLAN) na sua estratégia de optimização, apresentando resultados similares.

Sendo o objectivo primordial desta dissertação, estudar a optimização de sistemas energéticos híbridos e renováveis utilizando para isso a integração de funcionalidades atribuídas a redes inteligentes, tal como o armazenamento de energia e o consumo adaptativo, o estudo da integração de renováveis na produção de electricidade e o impacto das incertezadas associadas à previsão meteorológica, era um ponto fulcral a analisar. Embora em termos de produção eléctrica a Ilha do Corvo seja 100% dependente de diesel, já foram executados vários estudos para implementação de energia eólica e a facilidade na obtenção de dados de produção e de recurso solar e eólico, determinou que se recorresse novamente ao caso de estudo do Corvo para modelar a influência das incertezas do recurso na gestão do consumo adaptativo.

É demonstrado que as incertezas no recurso eólico têm maiores repercussões na gestão das cargas flexíveis, uma vez que estas são programadas para maximizar a absorção da produção eólica e têm um impacto directo na rede, diminuindo no entanto o seu impacto para menores cargas flexíveis. Relativamente às incertezas no recurso solar, para o sistema analisado, o seu impacto é menor pois está afecto a sistemas solares térmicos cuja função é o aquecimento de água, funcionando por isso como um amortecedor das incertezas, uma vez que armazena a energia solar, ao contrário do que acontece com a energia eólica que é transmitida directamente à rede. No entanto, para níveis baixos de armazenamento de energia térmica, isto é, de água quente nos tanques, o impacto das incertezas associadas ao recurso solar aumenta pois, pode condicionar a segurança de abastecimento de água quente ao utilizador final. Adicionalmente, uma maior precisão na previsão meteorológica, ou seja, com menores incertezas associadas, potenciará em sistemas renováveis híbridos uma maior penetração de energia renovável o que levará consequentemente a reduzir as emissões de CO_2 associadas.

Finalmente, a metodologia de optimização de cargas flexíveis em sistemas energéticos híbridos e renováveis, desenvolvida modularmente ao longo da tese e modelada para o caso de estudo da Ilha do Corvo, foi testada noutras escalas de micro-comunidades isoladas com diferentes características geográficas, perfis de consumo e sistemas energéticos.

A optimização do consumo adaptativo de sistemas energéticos isolados híbridos e renováveis, utilizando como cargas flexíveis o apoio eléctrico de sistemas solares térmicos, apresenta resultados interessantes para pequenas micro-redes, com capacidades instaladas menores de 20 MW, e com perfis

de consumo maioritariamente residenciais, especialmente quando a penetração de energia renovável é superior a 25% do total de energia produzida. O impacto dos sistemas solares térmicos, quando aplicados a 50% das casas, registou aumentos de 0.1% a 3% do consumo diário de electricidade, conforme se tratasse, respectivamente, de grandes sistemas (capacidade instalada superior a 20 MW) ou de pequenos (capacidade instalada menor que 20 MW). Os impactos positivos mais baixos foram registados em micro-redes, em que o perfil de carga é dominado pelo sector da indústria e/ou serviços, sendo o sector residencial uma percentagem pequena do perfil de carga diária. No entanto, esta metodologia demonstrou funcionalidades no controlo do pico de consumo e na redução das emissões de CO_2, que em comparação com outros sistemas de AQS alimentados com combustíveis fósseis, registou 88% menos emissões.

Conclui-se assim que a implementação de sistemas solares térmicos como solução sustentável e potenciadora de redução de emissões, optimização da operação da rede e controlo de pico de consumo, em sistemas energéticos isolados híbridos e renováveis é interessante para micro-redes com capacidade instalada menor que 20 MW, e especialmente em sistemas que tenham uma percentagem de produção renovável acima dos 25%.

Palavras-Chave

Consumo adaptativo; Armazenamento térmico; Redes inteligentes; Micro-redes isoladas; Sistemas energéticos híbridos e renováveis

Contents

List of Abbreviations and Acronyms

CDM	Clean Development Mechanisms
COP	Coefficient of Performance
DHW	Domestic Hot Water
DPP	Diesel Power Plant
DR	Demand Response
ED model	Economic Dispatch model
EDA	Electricity of Azores company
EV	Electric Vehicles
GA	Genetic Algorithms
GDP	Gross Domestic Product
GHG	Greenhouse Gases
HP	Heat Pumps
HRES	Hybrid Renewable Energy System
LGP	Liquefied Petroleum Gas
NPC	Net Present Cost
OECD	Organization for Economic Cooperation and Development
PDG	Private Diesel Generators
PV	Photovoltaics
RES	Renewable Energy Sources
ST	Solar Thermal Systems

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Chapter I
Introduction

The three pillars that support a sustainable energy system – energy security, environmental sustainability and economic development - are extremely hard to guarantee in small and isolated systems. The implementation of hybrid renewable energy systems that take advantage of the new smart grid features have the potential to promote self-sufficiency, energy use efficiency while reducing greenhouse gases emissions (GHG), and that is the underlying purpose of this work.

1 Motivation

Nowadays, there is still 15% of global population that lacks access to electricity, mostly in developing areas of the world, and especially in rural areas where the energy access is still sparse and limited, as demonstrated on Figure I.1.

Distributed and hybrid renewable energy systems can help to democratize the access to energy and contribute to the achievement of some of the Millennium Development Goals [1]. In particular, achieving sustainable energy for all - by providing essential and productive energy services in remote areas, such as enabling public lighting and electricity in schools after sunset or providing cooking facilities that do not depend on the collection of biomass (wood) - may help to promote social aspects as universal primary education, and empowerment of women [1] and thus contribute to the achievement of other development goals.

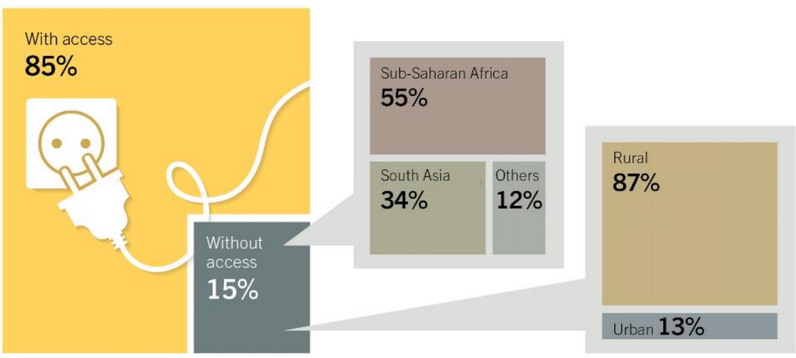

Figure I.1 - World Electricity Access by Region, in 2012 [2]

With the variability of fuel costs together with the international efforts to reduce GHG emissions, the investment on renewable capacity has been gathering interest both in developed and developing countries. As exemplified by Figure I.2, while in developed countries, the investment on renewables grew from 2004 to 2014 - with the exception of the years of 2009, 2012 and 2013, mainly associated with periods of economic crisis - in the developing countries it grew until 2014, except for 2013.

Multiple factors have contributed to the growth of renewable projects in developed and developing countries:

- in developed countries, projects have arose from the necessity to fight climate change, and reduce GHG emissions, meeting international environmental targets, reducing fossil fuels consumption, and increasing in this way the security of supply;
- in developing countries, the recognition of the importance of electricity and cooking energy access for remote and isolated communities, where hybrid systems – that integrate renewables and fossil resources – are the most cost effective solutions;
- the support of development banks have increased the number of clean and renewable investments in developing countries, since renewables begin to show more technological maturity and equivalent costs;
- the implementation of Clean Development Mechanism (CDM), until 2012, introduced by Kyoto Protocol [3], allowed developed countries to balance its GHG emissions investing on renewable projects in developing countries – this can explain the decrease from 2012 to 2013.

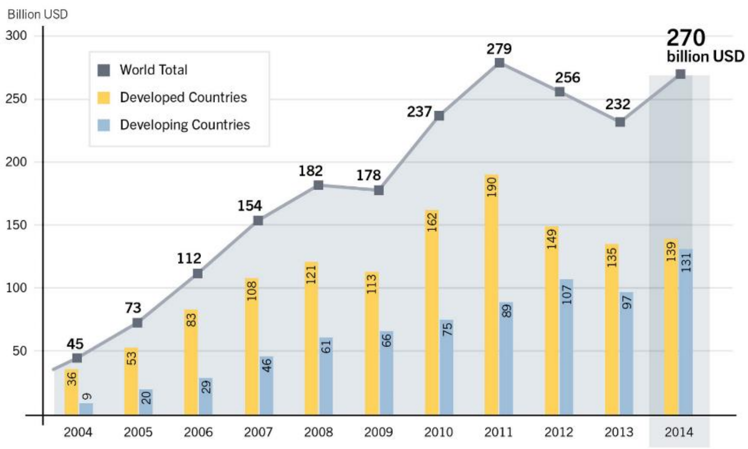

Figure I.2 - Global new investment in renewable power and fuels, in developed and developing countries, from 2004 to 2014 [2]

Figure I.3 presents the countries with some kind of policies and/or targets on renewable energy. As it can be observed, most of the developed and developing countries already present targets and policies regarding renewables. Some developing countries scattered in South America, Africa and Asia have either only defined policies but no targets, or only defined targets with no policies; Greenland, few islands in the north hemisphere and few countries in Africa, do not have policies nor targets defined.

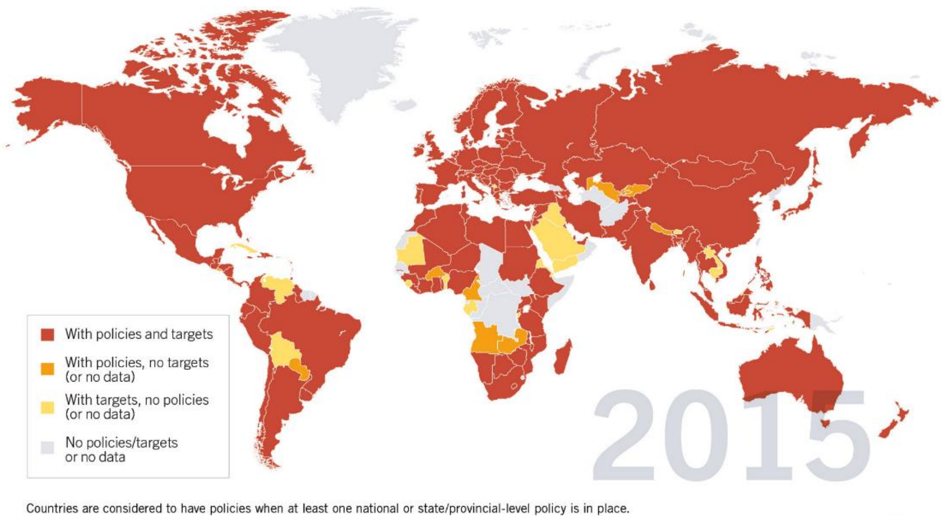

Figure I.3 - Countries with renewable energy policies and/or targets, in 2015 [2]

Figure I.4 presents the global share of renewable electricity production in the world, at the end of 2014. Despite the growing investments on renewables around the world, fossil fuels and nuclear still assure 77% of the electricity production, while renewables only present a contribution of 23%. Hydropower is the largest renewable source (16.6%), since is a well-mature and lasting technology with more than 100 years of implementation, while wind is a growing technology that represents 3% and bio–power (from biomass, biofuels, etc.) almost 2%. Solar photovoltaics are almost achieving 1% and all other emerging technologies as geothermal, concentrated solar power and ocean energy represent only around 0.4%.

Although these values seem encouraging for electricity production, when looking at primary energy consumption is still observed a predominance of fossil fuels, as presented by Figure I.5.

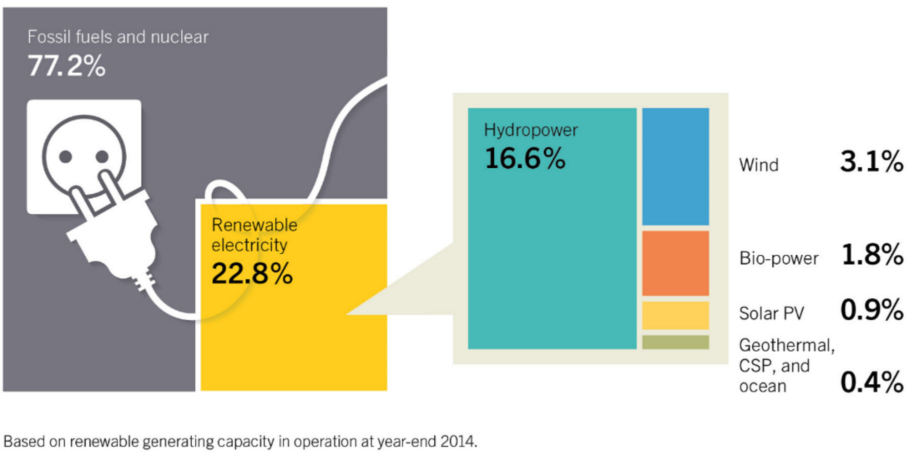

Figure I.4 - Estimated renewable share of global electricity production, in 2014 [2]

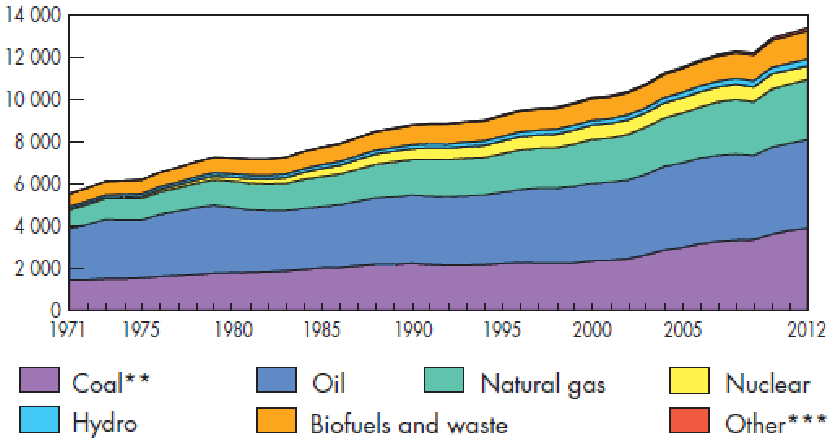

Figure I.5 - World total primary energy supply by type, from 1971 to 2012 (Mtoe) [4]

The consequence is the continuous global rise of CO_2 emissions at least until 2013, as seen in Figure I.6. However, despite the world's average annual 1.5% increase on energy consumption on recent years, coupled with an average 3% growth in the GDP, CO_2 emissions remain unchanged since 2013, which represents for the first time over the last decades that the economy grew decoupled from CO_2 emissions [5]. This can be explained by the increase of energy efficiency and renewable generation, especially from emerging world economies like China.

In Figure I.6 is still observable that, the main sectors that contribute more for CO_2 emissions are the power generation, industry and transportation sectors. The greatest is the power generation, responsible for more than 40% of the total emissions. In particular, the power generation in developing countries is responsible for almost 30% of the emissions.

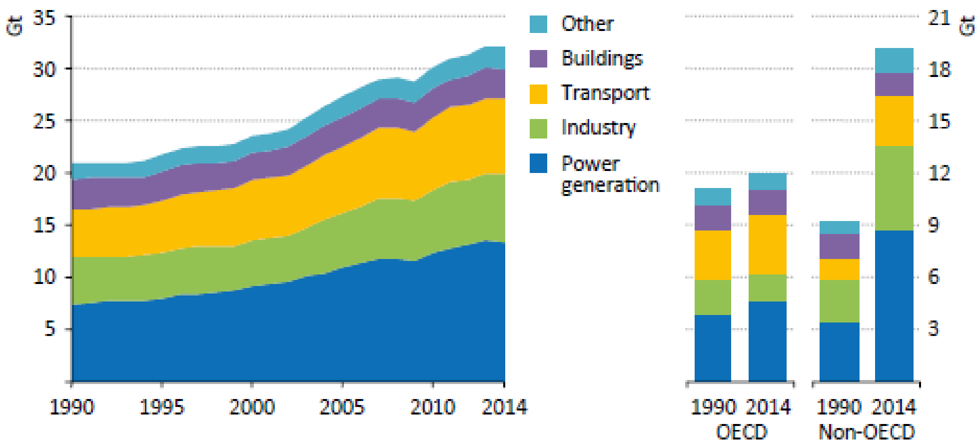

Figure I.6 - Global energy related CO_2 emissions by sector and region, from 1990 to 2014 [6]

Overall, and despite the growing investment on renewables and the recent stagnation of CO_2 emissions, the world primary energy still continues to be mainly based on fossil fuels (Figure I.5) and the CO_2

emissions almost triplicated on the power generation sector on Non–OECD countries, in 24 years (Figure I.6). This means that to reduce overall CO_2 emissions, one of the focus must be in the energy access in developing countries, but especially on remote and isolated communities. New systems are emerging or being converted, and there is the real possibility to influence local energy policy making by promoting the implementation of integrated and hybrid renewable energy systems.

2 Background concepts

In the following sections, the background concepts underlined in this thesis are introduced.

2.1 Integrated and Hybrid renewable energy systems

There is no strict definition of what an integrated energy system is. Ideally, an integrated energy system is one that takes advantages of the synergies between energy uses and energy vectors to increase efficiency. For example, a combined heat and power system where the waste heat from a electricity generation unit (from fuel or gas) is used for low-temperature applications, like pre-heating furnaces air, is a good example of an integrated energy system.

A hybrid renewable energy system (HRES) is one that couples, in the generation mix, more than on type of energy source, including renewable resources. It is seen as an opportunity to increase sustainability and security of supply, since it addresses the use of endogenous resources, as a way to improve energy efficiency and decrease external importations of fossil fuels. HRES are also becoming popular for isolated and small communities, although some operation questions arise, not only regarding the design, but also in terms of system's reliability in case of large renewable penetration.

2.2 Economic dispatch

One of the central issues to determine which units of a certain power system should operate at a certain time in order to meet a certain demand of electricity, is based on the variable operating cost of the different electric power plants [7]. This is called the electricity dispatch problem.

On a system, with multiple power plants, the technologies with lower operating costs are generally dispatched first, followed by the ones with sequentially increasing higher costs, as demand increases. There are other dispatch criteria that must also be followed, apart from the operation costs, such as the maximum capacity committed, the associated environmental emissions and the required reserve needed to guarantee the system's reliability.

The commitment of different power plants is such that is possible to answer the expected demand with a reserve margin, in order to enable a quick response to unexpected demand events. Normally, the units that assure the base load are typically the units with big inertia as thermal power plants or nuclear energy, while the peak increases are answered by quick response technologies with high power density, such as hydro or natural gas power plants.

On a hybrid renewable energy system, the availability of renewable energy resources is another important factor to take into account, as typically the operating costs of renewables are very low or null. This introduces a logic of full priority on the dispatch of renewables. However, the dispatch patterns are limited by a complex mix of technology time of response, balance between distribution and storage, grid stability, or even reservoir levels in the case of hydro power plants, etc. To keep the right balance between supply and demand, renewables are sometimes curtailed.

As seen, there are multiple criteria that can be considered for the electricity dispatch, however the model adopted in this work was the economic dispatch model with the unit commitment problem. This model is usually used for short-term electricity planning and consists on a minimization of the operation costs, taking into account all the systems constraints, as it is further explained on Chapter IV.

2.3 Smart grids and its capabilities

There are multiple definitions for smart grids: most definitions refer only to electricity grids while others present a more integrated approach of smart energy grids, either heat, gas or electricity.

Looking at different definitions, the *International Energy Agency* defines smart grids as "*networks that monitor and manage the transport of electricity from all generation sources to meet the varying electricity demands of end-users, being deployed at different rates (…) depending on local commercial attractiveness, compatibility with existing technologies, regulatory developments and investment frameworks*" [8]. The *European Technology Platform for the Electricity Networks of the Future* gives a more generic definition, stating that a smart grid is "*an electricity network that can intelligently integrate the actions of all users connected to it - generators, consumers and those that do both - in order to efficiently deliver sustainable, economic and secure electricity supplies*" [9]. Both definitions consider only the electricity grid.

The *Smart Grid Task Force* by the *European Commission* broadens the definition of smart grids to "*energy networks that can automatically monitor energy flows and adjust to changes in energy supply and demand accordingly, that, when coupled with smart metering systems, reach consumers and suppliers by providing information on real-time consumption, allowing consumers to adapt – in time and volume - their energy usage to different energy prices throughout the day, having economic benefits by consuming more energy in lower price periods*" [10]. The *US Department of Energy* participates of the same extended vison, adding also the goals that can be achieved through its implementation: "*(…) representing an unprecedented opportunity to move the energy industry into a new era of reliability, availability, and efficiency that will contribute to economic and environmental health*" [11].

Relying on the concept of using communication's information for a more efficient and reliable generation and supply, concepts like flexible demand, renewable integration, distributed generation, storage systems, and cross-energy vectors are integrated on the interaction of various agents and systems. Although smart grids are mainly thought for electricity grids, heat and cooling grids can also be smart, being the great challenge the integration of all these energy vectors.

Smart grids are desirable for system efficiency and reliability improvements, variable renewable energy integration and distributed energy resources, which can be driven by advanced metering infrastructures for demand response capabilities, enabling new services products to power costumer's decision and participation [8]. Thus, nowadays it is fundamental to consider the infrastructure that enable the smart grid in current and future planning of energy systems.

For isolated systems, the implementation of smart grid capabilities is also very relevant for the sustainability of the system, in order to:

- Increase the use of local resources, as renewables, for energy generation, instead of importing external resources, as fossil fuels;
- Use demand and peak control strategies, to make the use of the resources more efficient, such as storage and flexible demand;
- Reduce the variability and uncertainty associated to demand, but also to resource availability, through forecast and prevision;
- Manage and promote the optimization of generation dispatch, for optimal operation costs and reduction of CO_2 emissions – act locally, think globally.

2.3.1 Demand response

The potential to reschedule part of the electricity load on energy systems, but especially on isolated micro-communities, is seen as a promising opportunity to delay further investments on the power capacity of a grid.

The *European Network of Transmission System Operators for Electricity* defines demand response (DR) as *"a voluntary temporary adjustment of power demand taken by the end-user as a response to a price signal (market price or tariffs) or taken by a counter-party based on an agreement with the end-user"*.

If it is used for short periods (hours) it acts as a system power balance, providing economical optimization of the electricity demand. However if used during a longer period will also affect the energy balance in the power system and may also result in energy savings [12]. In this view, demand response can be driven by price incentives, or act like a contracted resource for power reserve.

Although demand response still presents technical and operability challenges, it can be considered one of the most promising smart grids' features, with potential on the following areas:

- Large scale integration of renewable generation, by shifting the load to hours with renewable penetration;
- Use of the thermal capacity of water heating or direct space heating or cooling, to shift the electricity consumption, than can be interrupt for a short period of time without interfering with the end-user comfort;
- Some industries with energy intensive processes that can function with market incentives to stop its manufacturing, if the market price of electricity is above a certain limit, and share the savings with the utility;
- Grid power balancing mechanisms.

Figure I.7 demonstrates multiple strategies of demand response, comparing a usual profile of consumption with one optimized with demand response. While *valley filling* can help taking full advantage of committed power plants or increase renewable penetration, *peak shaving* helps to decrease the peaks, avoiding the need to commit more generators, and so decreasing the operation costs. Finally *load shifting*, is a mix of the two previous strategies. These strategies consider the existence of enough systems' and load flexibility to shift some part of the loads to other periods.

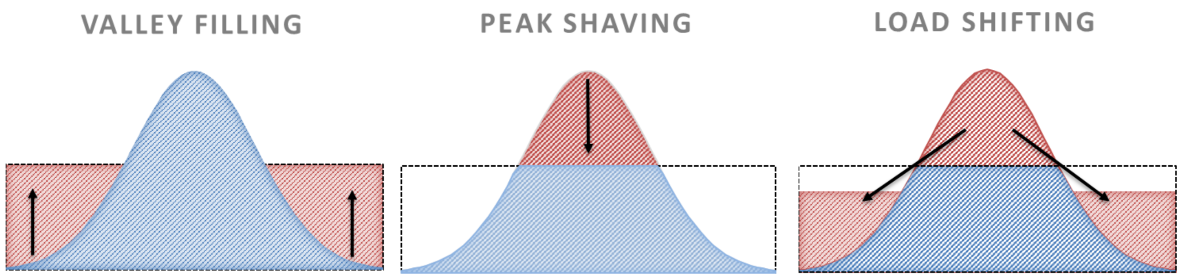

Figure I.7 - Demand response strategies

2.3.2 Energy storage systems

Energy storage is the key element for the growth of hybrid renewable energy systems, meeting different purposes on the planning of an energy system.

Figure I.8 presents multiple applications of storage systems, depending on their capacity, either in terms of power or energy density, and which can be used for power quality or to boost demand response capabilities. According to the purpose, different storage systems can act, in different ways [13]:

- for demand shifting and peak reduction purposes, storage can be done with thermal applications with capacities under 1 MW, for short periods (as minutes to one day);
- for variable renewable integration, storage can be assured, either by electricity or thermal applications, for capacities between 1 MW and 100 MW, also for short periods;
- if seasonal storage is the purpose, this is for longer periods (from days to months) and typically for capacities larger than 100 MW, electricity and thermal applications can be used;
- however, for system services, as spinning reserve, voltage support and frequency regulation, typically above 1MW capacity, electricity-only applications should be used.

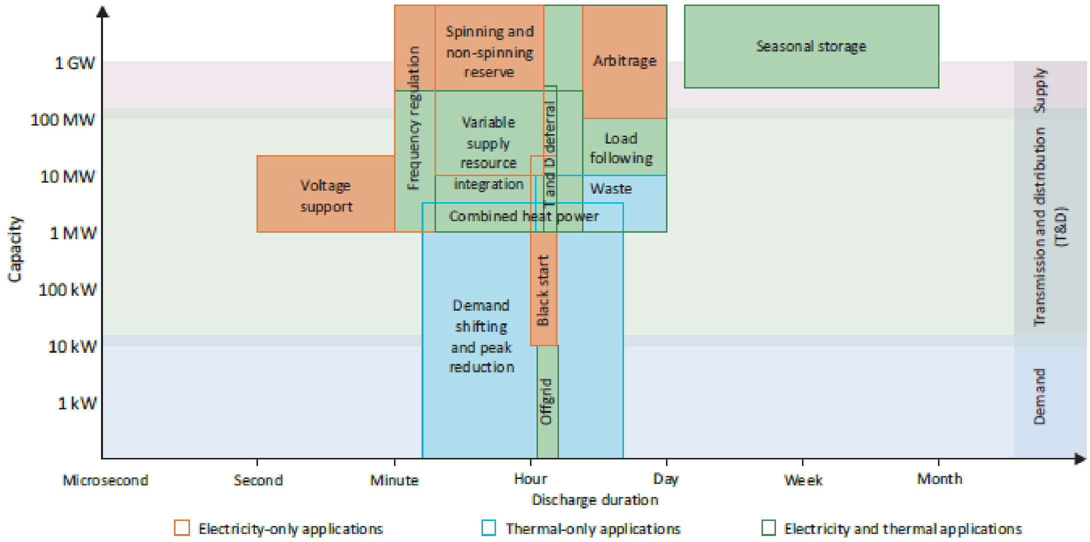

Figure I.8 - Energy storage applications, depending on power capacity and discharge duration [13]

The role of storage on isolated systems, especially with the presence of renewables, is of particular importance since it adds economic value to renewable generation, helping optimizing the grid's management and dispatch [14], and softening the impact of renewable availability uncertainties. Ideally, supply would have to match the demand, thus the capability of storing energy to provide a synchronized supply and demand, becomes the management core of an isolated grid, requiring planning ahead capabilities [15].

In this context, there are plenty of energy storage technologies that are currently being studied, that can be grouped by their scale:

- Large scale: pumped hydro, compressed air, power-to-gas, etc.;
- Small/local scale: chemical, electrochemical, electromagnetic;
- Small and large scale: thermal energy and some electrochemical.

Figure I.9 presents the suitability of the different types of technology, according to type of generation – conventional or renewable, and type of system services – transmission, distribution or costumer services. The outer line means that the technology is *suitable*, the intermediary line *possible* and the center *unsuitable*.

As it is possible to see, thermal storage is a solution that is suitable for conventional generation but also possible to renewable integration purposes, and it is suitable for costumer services, and possible for transmission and distribution purposes. This indicates that thermal storage, can be the driver for a systems' and consumer approach, and can be applied either for small or medium systems.

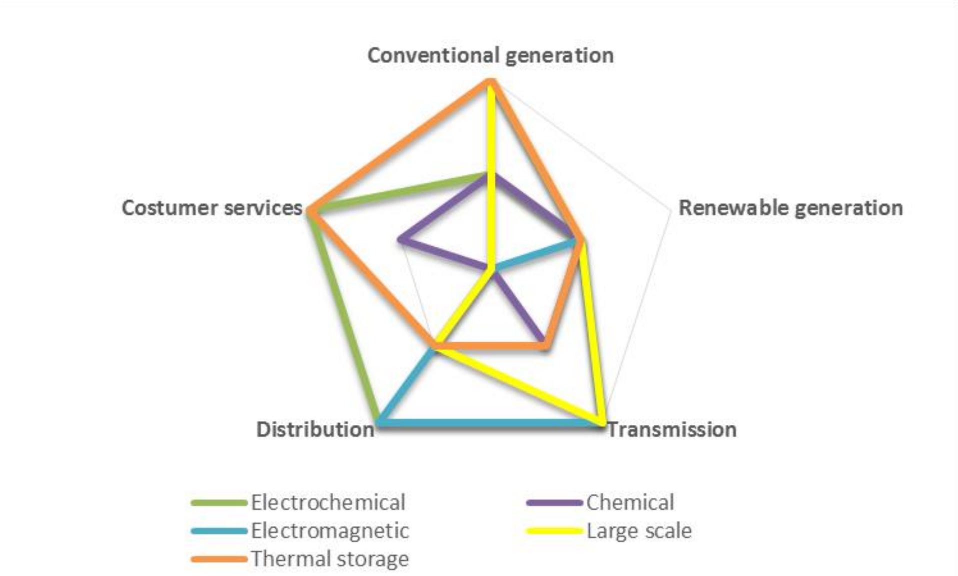

Figure I.9 - Ranking of suitability of energy storage technologies (adapted from [16])

Nevertheless, thermal storage, through sensible heat, in the form of *residential hot water heaters with storage* (Figure I.10) appears in the threshold of demonstration to commercialization, as reported in [17], [18] and [19]. However, to the best of my knowledge, there is still a knowledge gap regarding the use of residential thermal storage for commercial purposes that would be fulfilled integrating solar resource and grid dynamics. This is the main focus of this thesis.

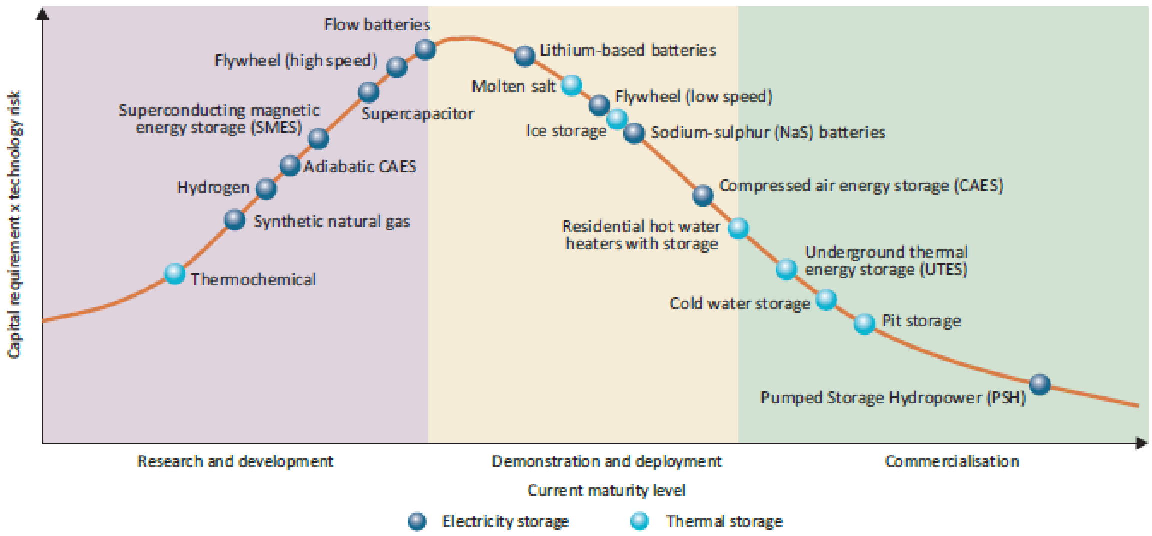

Figure I.10 - Maturity of energy storage technologies [13]

3 Research questions

The work presented in this thesis tries to answer which are the great development challenges for small and isolated communities, especially islands, and how they can be overcome through a smart grid approach. This topic maybe unfold in different research questions, as it follows.

1. What are the main socially, economic and energetic characteristics of small and isolated communities? Which factors limit or push their development?

While researching and trying to answer this question, the energy supply and demand of communities with isolated systems was analyzed. As the residential sector is normally the main consumer of these small and isolated communities, a solution had to focus on this type of demand [20]. The energy services are typically divided into four types: electric equipment, lighting, space heating and cooling and water heating. However, the residential sector has limited flexibility to change its loads to another period, usually taking advantage of lower production costs. Further, albeit the trend to hybridize the energy supply taking progressively advantage of a mix of endogenous resources to produce electricity, the supply of heat is still, in most cases, dependent on external resources, such as Liquefied Petroleum Gas (LPG) or diesel. This promotes an external dependency, and the CO_2 emissions associated with the heat supply remain unchanged.

At this stage, the most prompt solution is also to electrify the supply of heat, and integrate it on the islands' hybrid electric system. Of course, there could be multiple options to supply heat. However, focusing on the domestic hot water (DHW) is an interesting challenge, since the water heating is easily hybridized through the integration of electrified renewable systems, as it is the case of solar assisted heat pumps or solar thermal systems, and it opens the possibility to increase the flexibility of loads that can be shifted, with the thermal storage capacity of the hot water tanks. However, this arises an additional question:

2. Which is the electric impact of the implementation of electrified electric hot water system, as solar thermal systems and heat pumps?

Isolated communities normally struggle with power peak. This problem is especially important in larger communities, due to the existence of a tourism industry, which impacts in the demand with seasonal peak power oscillations. Nonetheless, the energy systems are normally designed to cope with these oscillations, using different power resources, normally thermal plants fueled by diesel that are quickly committed to cover that periods. However the demand growth has to be carefully manage in order to postpone the need for successive power generation capacity increases.

Moreover, if an isolated system opts for the electrification of the DHW supply to decrease the external dependence of fossil fuels, even if in part assured by solar energy, this could cause another problem – the increase of power peak at certain periods, in a scale that the current system might not handle it.

A conceivable strategy to cope with this problem is to assume the possibility to implement some kind of demand response on the electric system. Since we are considering small and isolated microgrids, there are no market conditions to establish flexibility on a decentralized way through price incentives, but rather promote demand response centrally managed, by the grid manager.

This introduces a new question:

3. How much of the operation costs of an isolated islands' energy system can be decreased by implementing thermal storage with demand response capabilities?

To test the best way to decrease the operation costs, multiple optimization hypotheses were assumed: different ways of optimizing the DHW backup loads - from heuristics, linear programing and genetic algorithms - but also different formulations of the optimization problem - in terms of number of systems switched on and off, or in terms of amount of energy.

Having tested and compared different formulations, the genetic algorithms optimization of the DHW systems total amount of energy, resulted on the best minimization of the operation costs, with lowest energy increase. However, for validation purposes, there was the need to compare these results obtained for the self-developed dispatch model with available other models:

4. How good can the current simulation tools model demand response?

Several energy modeling tools already include some feature to model the use of demand response strategies. Thus, another question that arose in the development of the work was how these tools perform compared with a specific model and how they could be improved to integrate demand response strategies.

To use these models for optimization purposes, resorts in general to average values of demand load, DHW daily needs and solar gains, not taking into account how exactly the balance between the hourly pattern of the hot water tanks and the solar radiation may impact the system. This led to question:

5. Which is the percentage of error of modeling demand response with average solar gains and real solar gains values for a particular day?

To analyze this, we need to introduce solar forecast dynamics and compare the two approaches regarding the use of solar gains: average values *versus* real values. As the intention was also to model hybrid electricity systems, wind energy was added to the energy system configuration of the case study. In this context a new question arose:

6. How much influence has the uncertainty of the renewables forecast, on the demand response dispatch? Does introducing wind power on the energy systems helps on the dispatch of the solar thermal systems' backup?

As done for the solar forecast before, we modeled the wind forecast taking into account the real case values for this new systems' configuration.

The case study used to answer all the previous questions was the isolated system of Corvo Island, in Azores, Portugal. So, the final question to be answered is to know the applicability and performance of this methodology outside the context of Corvo Island:

7. Can thermal storage play a central role on the optimization of the dispatch of isolated energy systems of different scales? For which conditions is the proposed approach valid and useful?

These are the research hypothesis that guided my research, leading me to answer them with the developed work, further explained in the Section 4.1.

4 Research strategy

The research strategy consisted in developing multiple models to answer the different research questions, from the technological electric impact to systems' operation optimization and renewables' integration, validating them, when possible, with real data from the case study of Corvo Island.

The choice of the Corvo Island as the main case study of a small isolated community is justified by the opportunity to engage in a close cooperation with Corvo Island authorities and utility, providing access to technical, statistical and operation data of the island. Moreover, the island is currently suffering an energy system transition towards sustainability and answering the research questions would provide useful information for the authorities to solve the current policy making issues.

In particular, Corvo Island started in 2010 the implementation of Solar Thermal Systems (ST) and Heat Pumps (HP) for domestic hot water (DHW) supply, replacing the LPG bottles supply, as a result of a previous work on the economic analysis of such implementation, developed by the Green Islands team, which I was part of [21].

This context proportionated the opportunity to study and develop a smart grid integrated energy framework for isolated microgrids and validating it with real data from Corvo Island. This result consists of an integrated energy systems' approach to assess demand response on isolated microgrids, through the use of the thermal storage capacity of DHW systems, in order to optimize the economic dispatch, reducing the operation costs, the peak load and the CO_2 emissions. Finally, this methodology was used to simulate other case studies in order to determine the bounds of applicability of the proposed methodology.

This section presents step-by-step the research strategy followed in this thesis, by presenting the work structure and linking it to the publications produced during the course of the research work.

4.1 Work structure

Figure I.11 presents the work structure by topics, corresponding each to a publication, developed further on the next subsections.

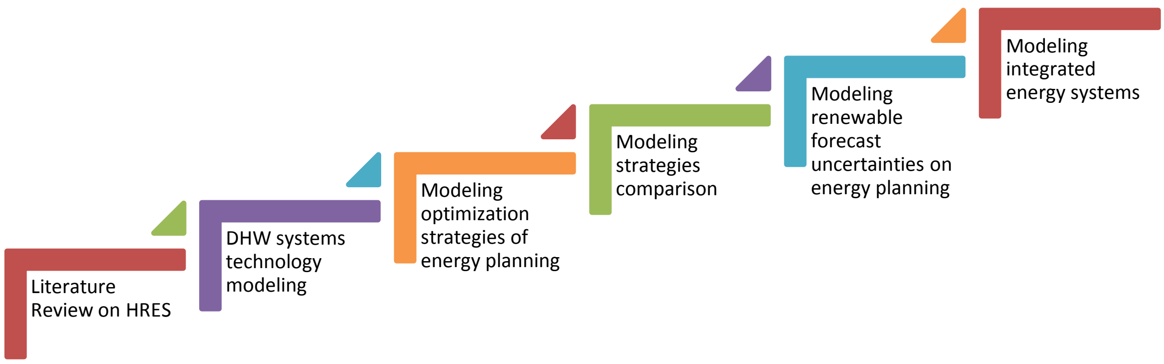

Figure I.11 - Thesis outline by topics

4.1.1 Literature review

As the first aim was to study small and isolated communities, it was decided to identify the main parameters that characterize these communities, in terms of energy systems, type of economic activities or even of location in the globe, and how these aspects interfere with the habits and economical capacities. The geographical or physical isolation was also approached, when comparing the energy systems' design of isolated islands and remote communities. In the process of reporting the state of the art of these communities, trying to identify their biggest energy challenges, a literature review of isolated micro-communities with hybrid renewable energy systems was developed [22].

The results report that HRES are increasing in isolated communities, as a way to provide security of supply, and consequently, many different methodologies, tools and feasibility studies have been done over the last decade to approach the design and implementation of hybrid systems on these communities.

4.1.2 Technology modeling

To model the impact of DHW systems on an isolated microgrid, Corvo Island was introduced as the case study. First, the electricity and heat demand of the island was analyzed, based on a local survey [23], and afterwards the supply data of heat and electricity was retrieved from the local utility for the years of 2010 to 2013. From the analysis of this load data, a typical year was found and was further used along the models for Corvo Island case study.

As the impact of the implementation of the new DHW systems was first notice in the grid, in the beginning of 2013, an hourly model to quantify the electric impact on the grid of the implementation of solar thermal and heat pump systems for domestic hot water supply was developed and validated for Corvo Island [24].

The relevant results of this new hourly model is the estimation of the impact on the grid of the implementation of ST and HP systems for DHW. However, in this study, this implementation is analyzed decoupled from the rest of the island' energy system, leading to the need of a global approach to the island' load dispatch.

4.1.3 Modeling optimization strategies of energy planning

After validating the model for the electric impact of electrified DHW systems, there was the need to develop a global model of the Corvo Island energy system, in order to evaluate the impact of such implementation on the system dispatch of the island and optimize it. The economic dispatch model based on a unit commitment problem was first introduced by [25]. This model was coupled with the model of the electric impact from the DHW systems implementation described in the previous subsection.

In [25], the ST electric backup was scheduled as a flexible loads to optimize the dispatch and minimize the operation costs by different demand response approaches: heuristics, linear programming and genetic algorithms. The genetic algorithms optimization was found to be the one that bests minimizes both peak load and energy load, and so, it was used as optimization strategy in the rest of the work.

4.1.4 Modeling strategies comparison

Although interesting results were achieved with the economic dispatch model optimization, it is very common to find scientific publications with self-developed models that are only valid for the specific case-studies they were developed to.

Corvo's utility had the will to implement in practice some kind of demand response actions, and in order to give a more relevant contribution on the optimization field, there was the need to test the performance of the demand response capabilities of our model against other available energy modeling tools usually used for energy systems modeling and optimization. For this purpose, a comparison of the demand response strategies of different modeling tools was done for Corvo Island case study [26].

A full analysis of the demand response strategies of HOMER [27], EnergyPLAN [28] and the previous developed economic dispatch model was taken. The comparison is done for the Corvo Island case study, where it is found that the developed model is the one that best reproduces the real operation dispatch data for Corvo, demonstrating however that tools like HOMER and EnergyPLAN are able to generate similar results, albeit with different DR strategies.

4.1.5 Modeling renewables forecast uncertainties on energy planning

After validating the developed economic dispatch model against other modeling tools, there was the need for the adaptation of the model to include renewable generation, as this is the natural transition for an isolated hybrid microgrid that is giving small steps towards sustainability. As the existent energy system in Corvo is still 100% fuel-based, wind generation was included on the model, taking into account the uncertainties introduced by the wind forecast. The solar forecast was also introduced for DHW generation, when planning the dispatch in one-day-ahead basis [29].

A sensitivity analysis on multiple parameters was made, such as frequency of forecast, forecast horizon and dispatch horizon, based on the comparison of the dispatch costs, wind generation absorption and DHW backup.

Also, with the idea of introducing the real time solar dynamics on the dispatch model, a comparison between two modeling approaches, comparing seasonal needs, was done [30]:

- the *dynamic* model, which is a modeling approach for smaller time scales (in the order of days to one week), which receives the solar forecast every 24 hours, and determines the hour at which the backup is needed, managing to optimize its dispatch until then, respecting the accumulation in the tanks;
- and the *average* model, which is a long-term modeling approach that uses seasonal backup averages and optimizes its dispatch without looking into the hour at which the backup is needed.

4.1.6 Modeling integrated energy systems

Until here, multiple models of optimization for demand response strategies and sensitivity analysis for the Corvo Island case study have been developed. However, to have an idea of the feasibility bounds of the proposed methodology, this work extrapolated the findings of the Corvo Island case study to other case studies with different parameters. To follow that purpose, the methodology of modeling the implementation of electrified DHW systems for optimizing the dispatch of isolated microgrids was tested on other isolated systems, with different characteristics that could influence the results found in Corvo.

With that in mind, the islands characterization parameters found in [22] where used to enumerate different case studies according to community scale, with different social, economic, climatic conditions and also different energy system configurations. As a result, an assessment of DHW systems' implementation on various types of isolated hybrid microgrids was produced, to know the feasibility boundaries of these methodology [31].

4.2 Publications

The work developed in this thesis resulted in the publication of five papers on international peer-review journals, and sixth one that is currently under review, and an additional Conference Paper, which are presented next, and relate directly to the work structure presented previously:

1. **Design and implementation of hybrid renewable energy systems on micro-communities: A review on case studies,** , by Diana Neves, Carlos A. Silva and Stephen Connors, published in the journal *Renewable and Sustainable Energy Reviews*, in 2014, [22];
2. **Modeling the impact of integrating solar thermal systems and heat pumps for domestic hot water in electric systems – The case study of Corvo Island**, by Diana Neves and Carlos A. Silva, published in the journal *Renewable Energy*, in 2014, [24];
3. **Optimal electricity dispatch on isolated mini-grids using a demand response strategy for thermal storage backup with genetic algorithms**, by Diana Neves and Carlos A. Silva, published in the journal *Energy*, in 2015, [25];
4. **Demand response modeling: A comparison between tools**, by Diana Neves, André Pina and Carlos A. Silva, published in the journal *Applied Energy*, in 2015, [26];
5. **Impact of solar and wind forecast uncertainties on demand response of isolated microgrids**, by Diana Neves, Miguel C. Brito and Carlos A. Silva, published in the journal *Renewable Energy*, in 2015, [29];
    a. **Demand Response on isolated island with solar forecast** by Diana Neves, Miguel C. Brito and Carlos A. Silva, presented on the 2nd International Conference on Energy and Environment: bringing together Engineering and Economics, 2015, and invited for publication on the Special Issue of the conference, on the *Energy* journal, [30];
6. **Assessment of DHW systems' implementation with demand response capabilities on isolated microgrids, using a smart grid approach**, by Diana Neves, André Pina and Carlos A. Silva, submitted to the *Applied Energy* journal, 2015, [31].

4.3 Outline of the thesis

The thesis is organized in seven chapters, as presented in Table I.1.

Table I.1 - Correspondence between papers and Chapters, referring its application and main topic

Chapter	Paper	Case study	Topic
II	1	Isolated islands and remote communities	Literature review
III	2	Corvo Island	Technology modeling
IV	3	Corvo Island	Modeling optimization strategies of energy planning
V	4	Corvo Island	Modeling strategies comparison
VI	5	Corvo Island	Modeling renewables forecast uncertainties on energy planning
VII	6	Several islands	Modeling integrated energy systems

Chapter II corresponds to *Paper 1*, where a literature review on the hybrid renewable energy systems of isolated communities is done. Chapter III presents *Paper 2*, where a model to quantify the electric impact of DHW systems on isolated microgrids is developed. In Chapter IV, *Paper 3* proposes and compares different optimization strategies to use demand response with the DHW backup loads, focusing on the genetic algorithms optimization. In Chapter V, *Paper 4* compares the performance of different HRES modeling tools when modeling demand response programs. In Chapter VI, *Paper 5* evolves the model to include solar and wind forecast information, quantifying the impact of forecast uncertainties. Finally, in Chapter VII, *Paper 6* implements the methodology developed along the thesis for different islands' in order to determine the conditions where the proposed methodology should be applied.

5 Conclusions and future work

The main contribution of this thesis is the development of a framework for modeling demand response on isolated and hybrid renewable energy systems, through solar thermal systems, which is of particular importance for the optimization of economic dispatch in a smart grid.

An overview of the main highlights of each chapter and future work is here presented.

5.1 Isolated hybrid renewable energy systems characterization and benchmarking

The reporting of HRES projects has still a long way of standardization, since the information given is disperse, often based only on estimations and differs with the focus of each project (environmental, economic, energetic, etc.).

For small scale HRES (supplying less than 100 000 people), the energy systems' configuration for islands and remote communities are different since they are designed for different scales of demand: on an island, the energy system is designed considering a minimal social structure, with services, schools, etc., that assure work and autonomy for that island; in remote communities, the electrification is done considering lighting at night and small appliances charging (cellphones or a community fridge, etc.) which of course leads to different HRES solutions.

The most frequent energy system configurations for islands are a combination of diesel, wind and photovoltaics, with the diesel playing a central role as backup, when the renewables do not assure the demand. For remote communities, the most frequent solution is diesel combined with photovoltaic and batteries, with the solar energy being stored in batteries along the day and consumed at night, and using a diesel generator for peak hours or for days where the solar radiation is not enough to fulfill the batteries.

The implementation of storage technologies continue to be a major challenge for these systems, both in economic and efficiency terms, which limits the penetration of renewables, hardly achieving more than 50% on isolated HRES. On the other hand, the use of methodologies or modeling tools is increasing as a way to evaluate more accurately the feasibility and performance of isolated systems. The use of these tools is more common in remote communities, where the collection of demand data is easier, than for scales where demand patterns are a mix from different economic activities.

From this review, four main aspects were identified to study and contribute on the design and implementation of HRES in small and isolated communities:

- better demand and renewable resource dynamics estimation;
- more reliable systems and with decreasing GHG emissions, using storage to decrease the use of conventional fuels;
- the use of methodological and simulations tools as a way to optimize the economic investments;
- promoting the inclusion of various agents (utilities, governments and users) as necessary to develop the systems towards self-sustainability.

5.2 Modeling domestic hot water systems

It was found that modeling the electric impact of domestic hot water systems, namely solar thermal systems and heat pumps, with a high-temporal model, has a significant impact on small isolated systems, such as the island of Corvo. With a share of 46% ST and 54% HP of the overall DHW systems, an increase of around 60% on peak demand and 7% on overall annual load is reported. The increase on the peak load is essentially due to ST systems, while the HP are responsible for the major increase on the overall load. To tackle this significant impact, which may cause a problem on the reliability of the energy system, various restrictions applied on the hour of the DHW backup were tested. The results show that it is possible to obtain a 36% reduction on peak increase compared to the original model, despite a slightly increase on the overall load, as well as economic savings, just by changing the backup control strategy using simple heuristics.

The electrification of the DHW supply coupled with restrictions on the hour of use of electric backup introduces annual savings of around 21.000€.

5.3 Different strategies to optimize the short-term energy operation

While testing the different strategies to optimize the daily dispatch of Corvo, through the optimal placing of flexible loads from solar thermal systems, it was found to be more efficient to use genetic algorithms as demand response optimization strategy, for minimizing the dispatch costs and energy consumed, than using heuristics or linear programming. Although the strategy that bests minimizes the dispatch costs is the linear programming, it introduces an increase of almost 12% on the energy load, while genetic algorithms optimization presents 1% savings on dispatch costs, compared to simple implementation of DHW without demand response actions, and the best match between peak increase (limited by the installed capacity), total energy demand (related to the increase of imports of primary energy to the island, as fossil fuels) and dispatch costs.

When comparing different formulations of the problem - considering the number of solar thermal systems switched on *versus* amount of energy (flexible loads) to reschedule – the best results were found for the amount of energy formulation. When evaluating GA parameters, the best results were achieved for higher numbers of population and generations. The GA formulation is easily scalable for other problems of demand response.

5.4 Demand response optimization strategies in different modeling tools

Most of new developed models in literature are thought for a specific case study, lacking a comparison with other available tools that are able to model the same problem. This fact led us to compare the demand response strategies on the most popular HRES modeling tools, namely HOMER and EnergyPLAN, with the self-developed economic dispatch optimization model.

Three scenarios were designed for comparing the economic dispatch model and the demand response strategies using the case study of Corvo Island, a diesel powered energy system. The self-developed model presented the dispatch costs closest to real operation data, which could be expected since the model was developed considering the specifications of Corvo, while the two other tools – HOMER and EnergyPLAN - had similar but less accurate results. Further, the developed model using GA for optimizing demand response showed that it would be possible to achieve 0.3% savings on dispatch costs, while the demand response strategies of HOMER and EnergyPLAN showed smaller savings (less than 0.1%) compared to the fixed scenario. The main reason found for such small difference resides on the fact that these two tools are prepared to optimize demand response in presence of renewables electricity surplus, which in the case of a 100% fuel-based energy system is not.

Thus, demand response modeling still presents technical and modelling challenges. In particular, modeling tools need to cope with more flexibility either on the formulation or time resolution.

5.5 The impact of renewables forecast uncertainties on demand response

In *on-demand* supply systems, where thermal generators respond immediately to the demand, there is the need to deal with uncertainty from the demand side to estimate the needs. However when modeling the integration of renewable energy into an energy system, new uncertainties arise associated with the renewables resource forecast and availability.

To access the impact of renewable forecast uncertainties on demand response strategies, Corvo Island was modeled as an integrated energy system with a wind power plant for electricity generation, and solar thermal systems for heat generation. Therefore, the wind and solar resources forecast were modeled with a persistence model. Uncertainties related to the demand side were not considered in this model, since the objective of the study was to characterize the uncertainties from the supply side. With this approach we intended to test two premises: how much forecast uncertainties influence the economic dispatch, and if demand response strategy with thermal storage can help to absorb more wind generation, decreasing the demand of fossil fuels for electricity generation.

Results for Corvo Island case study showed that solar and wind forecast uncertainties influence the economic dispatch and demand response management, albeit at different levels. Solar forecast uncertainties are found to impact less, since they do not have instantaneous impact on grid (solar forecast is used to predict only the DHW electric backup needs), although it becomes crucial when the thermal storage is low. Since DHW backup is designed to take full advantage of the presence of wind generation, the wind uncertainty impact is dissipated with decreasing flexible loads. However, this also depends on the forecast horizon that is used, and the uncertainties have lower impact for smaller horizons, as expected.

From the comparison between the *average* approach and the *dynamic* approach (real values) to solar gains (see subsection 4.1.5), it was observed 4% savings on dispatch costs in winter, if the dynamic model is considered instead of using average values of DHW backup needs, representing also a higher percentage of avoided CO_2 emissions.

5.6 Assessing DHW systems with demand response capabilities for different scales of isolated microgrids

As the methodology to use DHW systems as demand response agents to optimize the dispatch of an isolated microgrid was developed and tested for Corvo case study, a final assessment was done to understand how the methodology could be applied for other scales and type of islands with HRES. The islands chosen had multiple geographical locations, number of population, demand per capita, type of load profile (according to main activities) and type of HRES (dependent on the economic structure), annual demand and peak load [14].

From this work is concluded that the implementation of ST systems impacts from 0.1% to 3% on the daily average demand, considering larger (>20 MW power installed) and smaller islands (<20 MW power installed), respectively.

Small islands with an installed capacity lower than 20 MW, benefit from implementing demand response on the solar thermal systems, as it brings significant advantages in the islands' peak control and CO_2

emission reductions. This is especially relevant in the islands with renewable penetration higher than 25% of overall generation. However for very small islands where the energy system is dimensioned for a very low intensity demand (as the ones found for remote communities, as seen in Section 5.1) it is very difficult for the system to cope with such implementation.

Bigger islands where the sectors of services and industries are the main consumers, the use of demand response strategies at the residential level will not have a significant economic impact.

Nevertheless, comparing the use of solar thermal systems for domestic hot water will result on environmental gains with 88% less emissions than other fuel powered domestic hot water systems.

6 Future work

Starting from a systems' planning approach, the work presented here advances the scientific knowledge on the use of solar thermal systems as demand response agents, to optimize the economic dispatch of isolated grids, from the grid manager point of view. Nonetheless, this work could be further developed, mainly in two directions:

- Study the technology integration and communication protocols needed on solar thermal systems, to be managed centrally;
- Exploring the user side, namely regarding economic savings and/or incentives that could advent from rescheduling the solar thermal backup for off-peak hours. For this purpose, the author is developing a product to allow the final user to control the backup of its solar system, according to solar forecast and energy stored in the tank.

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Chapter II
Design and implementation of hybrid renewable energy systems on micro-communities: a review on case studies

Abstract

In a world struggling for sustainable access to energy for all, renewable energy systems can be a solution to implement on isolated micro-communities. However, such an implementation is still a challenge.

This paper aims to review several types of projects developed in different micro-communities, namely small islands and remote villages, both in cases of real implementation or only evaluation studies. To do that, we analyzed documented projects in micro-communities with less than 100,000 people. We looked into different indicators related to island characterization, energy demand, and proposed technical solution, in order to identify the determinant factors for the success of the implementation and how do they differ for islands and remote villages.

In islands, the main factors that influence the achievement of higher percentages of renewable source (RES) are the design of the existing energy system, the presence of a reliable energy storage system and the profile of the electricity demand, especially the occurrence of peak demand and seasonal oscillations. In general, the more popular configuration is a diesel/wind/photovoltaic.

In remote villages, higher percentages of RES are meet more easily in cases of very low demand, unstructured previous electric supply and the capability of using batteries as storage. The more popular configuration is the photovoltaic/diesel/batteries.

Having detailed demand information, estimates from the local renewable resources and the adequacy of the storage system are critical aspects for the system's design and its successful and reliable application.

This review also shows that the data reported in many different case studies is often incomplete, which makes it hard to benchmark and evaluate the different projects. Thus, this paper proposes a methodology to report the data regarding the design and implementation of HRES, to enable the comparison of future projects and contribute to the discovery of new insights about the implementability of these systems.

Keywords

Hybrid renewable energy systems; Isolated micro-communities; Off-grid islands; Remote villages

1 Introduction

There are 1.2 billion people in the world (20% of world population) that still live without access to electricity [1]. The international community is concerned and seems committed to minimize this inequality of energy services between OECD and developing countries. Table II.1 shows the universal modern energy access case for the 2010-2030 Scenario [1], which suggests that 60% of the additional generation capacity and 63% of the total investment budget will be done on mini-grids and off-grid systems. This indicates that off-grid and mini-grid systems are emerging as the solution to improve welfare and socio-economic development of small isolated communities, as islands and remote villages.

Table II.1 - Projections from the Universal Modern Energy Access Case Scenario for 2010-2030 [1]

	Isolated off-grid	**Mini-grid**	**Grid Connections**
Distribution of the additional generation of 952 TWh	18%	42%	40%
Distribution of the additional investment of 700 billion $	20%	43%	37%

Many of these communities spend over 20% of their income on energy [2], and due to the increasing costs of fuel generators (e.g. diesel) [3], the use of hybrid systems that incorporate renewable energy resources is a way to keep the systems more reliable and sustainable. These small communities are normally characterized by different types of constraints that span from small size, remoteness and vulnerability to external shocks (demand and supply side), narrow resource and exposure to global environmental challenges [4].

To help developing small and micro-communities, there are some interesting international cooperation programs running, with special focus on the development of renewable energy systems, such as: Small Island Developing States Network [5]; Energy Development in Island Nations [6]; ECOWAS for Renewable Energy and Energy Efficiency (ECREEE) [7]; European Island Network on Energy and Environment [8]; Green Islands Project [9]. We have also register an increase of forums [10] and joint initiatives [11], that aim to spread knowledge on renewable systems, case studies and sustainable energy policies.

This review intends to map the *state of the art* of Hybrid Renewable Energy Systems in isolated micro-communities, especially in islands. This work aims to understand the system's configuration, the main characteristics of the electricity demand and its dynamics, and the difficulties of implementation. Parsing the main limiting factors, we intend to pursue the development of a methodology to implement HRES with higher renewable penetration, allowing more autonomy, without forgetting reliability of supply and economic sustainability. We recognize that only an organized and standardized methodology of approach to HRES can bring clearance and success to the design of these systems. To achieve that, we have to take into account financial aspects, monitored and estimated demand, and an accurate forecasting of renewable potential.

This review also shows that the data reported in many different case studies is often incomplete or not so relevant, which makes it hard to benchmark and evaluate the different projects. Thus, this paper proposes a methodology to report the data regarding the design and implementation of micro-community hybrid renewable systems. This enables the comparison and benchmarking of future projects against the cases presented here and contribute to the discovery of new insights about the implementability of this type of system.

2 Review approach

We listed various projects on micro-communities (islands and remote villages) with less than 100,000 people or equivalent in households, aiming to focus on smaller and isolated communities, with less than 10,000 people.

Later, we looked at the energy demand in these small communities and found that, albeit tourism is a relevant activity in most of the cases above 2000 inhabitants, there is few representativeness of other energy intensive sectors, such as industry or services. Thus, electricity demand in residential sector represents the largest share of total energy demand, which explains why this study focuses only on electricity demand.

Through the analysis of multiple case studies, we defined a list of indicators (Table II.2) that we consider necessary to understand the energy system structure. These indicators take into account the community characterization and some technical data of the hybrid system that have been studied and/or implemented. With these indicators, we tried to analyze the implementation and success of these HRES, also taking into account the optimization methodologies' used to maximize renewable penetration if used in the system design.

Table II.2 - Characterization of indicators

Community Characterization	**Renewable Hybrid System Details**
Geographical site	Percentage of renewable energy provided by the system
Population	Type of energy supply
Economic activity	Type of storage
Water resource	Methodology or software to optimize system design
Type of grid connection	Application
Electricity demand	

As each case study has its own specific goal (economic analysis, energy reliability, validation of a certain methodology, etc.) we encountered some difficulties to systematize the information (Table II.2) and characterize each case study accordingly. Occasionally, it was necessary to proceed with a web search on local electricity companies' annual reports and other sources to complement the information from scientific publications.

2.1 Community characterization

The location of the community (continent and country) is important to know as electricity demand patterns differ with geographical site and cultural habits. The population is an important indicator to understand how demand per capita differs from region to region, especially between the Northern hemisphere countries and South ones. The economic structure also affects the energy demand, thus we considered the existence of the economic activities of Farming, Fishing and Agriculture (primary sector), Industry (secondary sector) and Tourism and Services (tertiary sector).

In the particular case of islands, water resource can be scarce or inexistent, especially those in dry climates. Due to geographical isolation, the water may be imported (in general using boats increasing largely their energy bill) or use desalinization processes, which are large energy consumers, and therefore may have an important weight in electricity demand of small communities without industry sector.

Characterizing the systems as stand-alone or grid-connected systems is important to understand some implementation choices regarding renewable penetration and system operation. On stand-alone projects, normally we find technical studies and economic evaluations that are more accurate, as the systems have to be capable to respond to peak load by themselves, even when there is few renewable resources available, and there is the need for a reliable backup and storage systems. Knowing the type of grid connection, is possible to consider different scenarios and study the improvements of adding HRES to the grid.

Finally, having a detailed characterization of yearly electricity demand for each case study, allows us to understand the magnitude of the consumption needs in these communities as a reference to designing the systems that can respond to them. Having also the demand growth rate is important, as this type of systems has to be reliable (and so, well dimensioned) and cannot collapse with an increase of the demand due to the provision of more services to a certain community.

2.2 Hybrid renewable energy system details

To describe the type of HRES, we start by considering the percentage of renewable penetration on the total delivered energy. This provides us with an idea of what kind of system it is: mainly renewable with some kind of backup or based on a previous supply system with some additional support from renewables.

The description of the resources availability is important to find patterns of application and success of these hybrid systems, and to understand the preference of certain technologies over others.

The description of the storage system works as an indicator of the *state of the market,* and the (dis)trust that experts put on certain technologies. For example, the type of storage technologies used on stand-alone systems, which normally are exposed to exhausting life cycles, gives us an idea of the real level of reliability on renewable-storage coupled systems.

In some studies, we see the use of some optimization tools to obtain the system design, using a certain methodology or software. Its use allows the definition of the best possible option to achieve the HRES with predefined goals at minimum cost. With optimization tools becoming more popular, it is interesting to see its effectiveness through the comparison and/or validation before and after the project.

In this perspective, we categorize the case studies regarding its application. Only with real case studies and its results, we can step forward to validate the models, facing *in situ* problems and learn from them.

3 Comparative review

In this section, we present the comparative review of the case studies analyzed, based on the indicators previously presented for two types of locations: islands and remote villages.

3.1 Islands

The values represented in Table II.3 were found on a large literature review, between scientific papers and government and electricity companies' data. In some cases, national or regional values of demand per inhabitant had to be taken into account, to estimate the island demand.

3.1.1 Island characterization

Looking at Table II.3, we find that this type of projects take place all across the world, though most of the cases are in European islands. In terms of population, though we considered studies up to 100,000 inhabitants, most of the cases have been done to smaller populations (<10,000).

The main economic activities carried out in these islands belong in general to the primary sector, this is, farming, fishing and agriculture for self-sufficiency. In larger islands (> 2000 people), we start to find more tourism activities than subsistence ones, which has an impact on energy consumption. Taking, as last example, the case of Gotland, Sweden, we also see that the existence of industry (concrete production) influences heavily the energy demand values.

Table II.3 - Island case studies comparative review

Island characterization								**Energy System Characterization**						
Continent	**Name/ Country**	**Population** [number]	**Economic Activity**	**Water Resource**	**Type of grid connection**	**Demand** [MWh/ year]	**Demand Growth Rate** [%/year]	**Type of previous supply**	**RES** [%]	**Type of Supply**	**Type of Storage**	**Methodology / Software**	**Application**	**Study**
Europe	Community in Utsira, Norway	212	N/A	N/A	Connected	246	N/A	Grid	50-65%	Wind (stand-alone system)	Hydrogen gas storage + fuel cells	TRNSYS + HYDROGEMS	Applied	[12]
Europe	Corvo, Azores, Portugal	425	Farming, fishing	rainfall collection	Isolated	1400	7.20%	Diesel power plant (DPP)	70%	Wind + PV + DPP	Flywheel	HOMER	Being applied	[13][14][15]
Europe	Ventotene, Italy	580	Tourism	Imported	Isolated	531	N/A	Diesel power plant + Photovoltaic	60%	Wind + PV + Wave + DPP + (ST+EE+DSM)	H2 Fuel Cells	TRNSYS	Evaluation only	[16][17]
Oceania	Chatham Islands, New Zealand	600	Farming, fishing	N/A	Isolated	2370	N/A	Diesel power plant	47%	Wind + DPP	N/A	N/A	Being applied	[18]
Asia	Nolhivaranfaru, Maldives	650	Fishing & tourism	N/A	Isolated	111	12%	Diesel power plant	57%	Wind + DPP	N/A	HOMER	Evaluation only	[19]
Europe	Mljet, Croatia	1111	Farming, fishing, agriculture & tourism	Desalinizat ion + imported	Connected	4640	7%	Grid	50%	Wind + PV (stand-alone system)	H2 Fuel Cells	H2RES	Evaluation only	[20]
Europe	Pellworm Island, Germany	1200	Farming & tourism	N/A	Connected	11250	N/A	Grid	100%	Wind + PV + Biogas	N/A	N/A	Applied	[21][22]
North America	Fox Islands, Maine, USA	1550	Fishing	N/A	Connected	11793.6	N/A	Grid	74%	Wind + Grid	N/A	N/A	Applied	[23][24]
Europe	Kithnos, Greece	1600	Tourism	N/A	Isolated	5630.2	N/A	Diesel power plant + Wind + Photovoltaic	33%	Wind + PV + DPP	Batteries	Simulink	Applied	[25][26][27]

Table II.3 - Island case studies comparative review (cont.)

Island characterization								**Energy System Characterization**						
Continent	**Name/ Country**	**Population** [number]	**Economic Activity**	**Water Resource**	**Type of grid connection**	**Demand** [MWh/ year]	**Demand Growth Rate** [%/year]	**Type of previous supply**	**RES** [%]	**Type of Supply**	**Type of Storage**	**Methodology / Software**	**Application**	**Study**
Oceania	King Island, Tasmania	1723	Tourism, industry, fishing & farming	N/A	Isolated	12870	N/A	Diesel power plant + Wind	65%	Wind + PV + Biodiesel + DPP	Batteries	N/A	Being applied	[28][29]
Oceania	Norfolk Island, Australia	2302	Tourism	N/A	Isolated	7900	N/A	Diesel power plant	60%	Wind + PV + DPP	H2 Fuel Cells	N/A	Evaluation only	[30]
Oceania	Rotuma Island, Fijis	2500	Farming, fishing	Rainfall collection	Isolated	876	N/A	Diesel power plant	N/A	PV + DPP	Batteries	HOMER + surveys	Evaluation only	[31]
Europe	Salina Island, Sicily, Italy	2504	Tourism	N/A	Isolated	10859.5	1.8%	Diesel power plant	18-40%	Wind + PV + PDG (home systems)	N/A	TRNSYS	Evaluation only	[32]
Asia	Pangan-an, Philipines	2800	Fishing	N/A	Isolated	30.2	N/A	Private diesel generators + Photovoltaic	80%	PV + PDG	Batteries	survey	Applied	[33]
Asia	Neil Island, India	2806	Agriculture, farming	field water, rainfall collection	Isolated	843.15	N/A	Private Diesel generator	100%	PV + Biogas + Biomass gasification	Batteries	local data + survey	Evaluation only	[34]
Europe	Flores, Azores, Portugal	4099	Farming, fishing & services	N/A	Isolated	11370	3.80%	Diesel power plant	54%	Wind + Hydro + DPP	Flywheel	N/A	Applied	[35]
Europe	Samso, Denmark	4300	Agriculture, farming & tourism	N/A	Connected	27000	N/A	Grid	100%	Wind + Grid	N/A	N/A	Applied	[36][37][38]
Europe	Graciosa, Azores, Portugal	4879	Farming, fishing & services, tourism	N/A	Isolated	13090	3.90%	Diesel power plant + Wind	70%	Wind + PV + DPP	Batteries	N/A	Being applied	[35][39]

Table II.3 - Island case studies comparative review (cont.)

Island characterization								**Energy System Characterization**						
Continent	**Name/ Country**	**Population** [number]	**Economic Activity**	**Water Resource**	**Type of grid connection**	**Demand** [MWh/ year]	**Demand Growth Rate** [%/year]	**Type of previous supply**	**RES** [%]	**Type of Supply**	**Type of Storage**	**Methodology / Software**	**Application**	**Study**
Europe	Porto Santo, Portugal	5000	Tourism	Desalinization	Isolated	40000	1.90%	Diesel power plant + Wind	45%	Wind + DPP	N/A	RenewIslands	Evaluation only	[40]
Asia	Peng Chau, Hong Kong	6000	Tourism	N/A	Connected	21750	2.0%	Grid	100%	Wind + PV + Grid	N/A	N/A	Evaluation only	[41]
Europe	Karpathos, Greece	6511	Tourism	N/A	Isolated	25956.4	4.7%	Diesel power plant + Wind	20%	Wind + PV + DPP	N/A	HOMER	Being applied	[42]
Europe	Mykonos, Greece	10000	Tourism	N/A	Connected	43612	N/A	Diesel power plant + Wind	18%	Wind + PV + DPP	N/A	N/A	Being applied	[43]
Europe	El Hierro, Canary Islands, Spain	10000	Tourism	Desalinization	Isolated	41530	N/A	Diesel power plant	75-80%	Wind + DPP	Pumped Hydro	N/A	Being applied	[22][44][45]
North America	Bonaire Island, Netherlands	14500	Agriculture & tourism	N/A	Isolated	75000	N/A	Diesel power plant	40-45%	Wind + Biodiesel + DPP	Batteries	N/A	Applied	[46]
Africa	Sal, Cape Verde	20000	Agriculture, fishing & tourism	Desalinization	Isolated	29092	4.90%	Diesel Power Plant	9%	DPP + wind + solar	N/A	N/A	Applied	[47]
Oceania	South Tarawa, Kiribati (atols)	40311	Agriculture, fishing	ground water	Isolated	8062.2	28%	Petroleum + Biomass + Photovoltaic	25%	PV + Biomass + Petroleum	N/A	N/A	Applied	[48][49]
Europe	Gotland, Sweden	57000	Agriculture, Farming, Industry, Tourism	N/A	Connected	754000	N/A	Grid	25%	Wind + PV + Biomass + Grid	N/A	N/A	Applied	[50]
Asia	Kinmen Island, Taiwan	84570	Tourism, services	N/A	Isolated	254452.3	4%	Diesel power plant	34%	Wind + PV + DPP	N/A	N/A	Evaluation only	[51]

Normally we could expect an increase of energy demand with population, but as we can see in Figure II.1, only in smaller communities (under 10,000) that is true. When we account with larger communities, this relation is not linear anymore. There we see, for example, that South Kiribati has a demand of only 8062.2 MWh/year for a population over 40,000 people, compared for instance with Gotland, Sweden, where the demand is 754.000 MWh/year for a population of 57,000 people. This discrepancy is relate to the differences in existing economic activities, geographical site and eventually cultural aspects.

In the zoom of 10,000 people, in Figure II.1, we see that albeit some dispersion, we can assume a linear relationship between the demand and the population. The exceptions are:

- the islands which present higher demand per capita are all located in developed countries (four in Europe and one in Australia) and they all have tourism activity; Porto Santo has also a water desalination power plant, which explains the higher consumption;
- the islands which present lower consumption are located in Asia and Oceania, in developing countries where the economic activities are still from the primary sector.

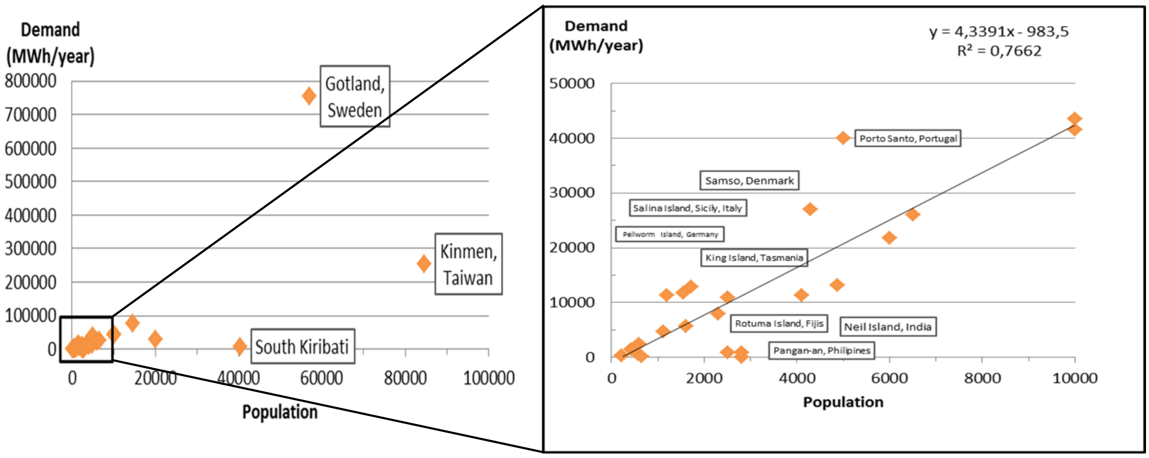

Figure II.1 - Electricity Demand versus population (whole range up to 100,000 population and zoomed in to 10,000)

In Figure II.2, we can compare how electricity demand per capita changes by continent. The demand per capita per year on the European islands is on a range of 1000-14,000 kWh/capita/year, showing that Europe divides itself in different patterns of demand due to its geographical, cultural and economic heterogeneity. On the other hand, if we look to Asia we see a smaller range of 30-4000 kWh/capita/year, where typically we have very low demand on islands isolated by the ocean, and larger islands connected to the main country, where the access of goods is easier and with higher consumption. Also in Oceania, this demand is influenced by the fact that they are part of the Commonwealth of Australia (Norfolk Island, King Island, Chatman Island) or are an isolated island country (Fiji, Kiribati), leading to a discrepancy of 3000-7500 kWh/capita/year and 200-300 kWh/capita/year, respectively. In North America, we find the difference from Caribbean Countries to Northern States, which imply a difference of 5000-8000 kWh/capita/year, being America the continent that has the highest beginning range. For Africa we used only one case study (Sal, Cape Verde), that presents a demand about 1500 kWh/capita, that due to tourism and the existence of a water desalination plant it is not so low as we could expect (as the rest of Africa), but still is very low compared to other continents.

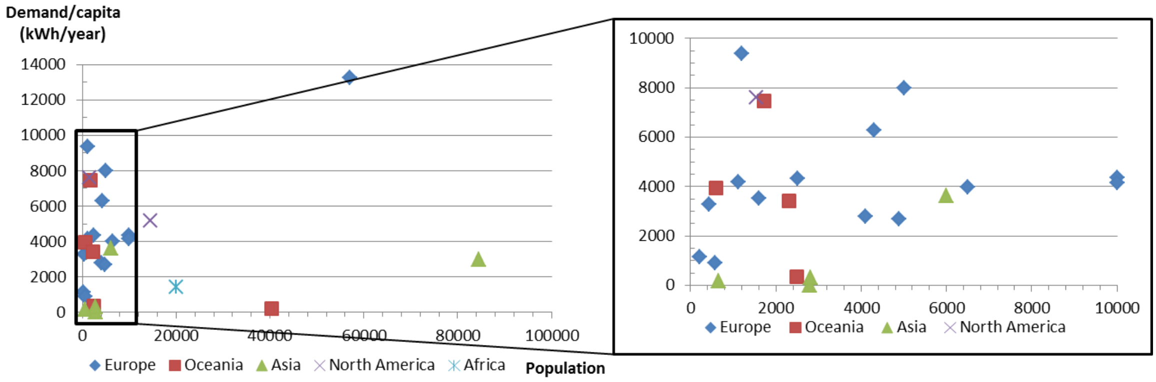

Figure II.2 - Electricity demand per capita according to geographical site and population

3.1.2 HRES characterization

Regarding the type of existing supply systems, we see in Table II.3 that diesel power plants (DPP) dominate the supply (39%), except for grid-connected cases (25%), where the energy mix depends largely on the mainland grid. However, we can observe already a significant number of hybrid systems of DPP/Wind (18%). Other combinations of hybrid systems, depending on the type of endogenous resources, are available in each case and consider mixes of different renewable sources like wind, solar photovoltaic (PV) and biomass. We can also see that in some remote islands with very low demand, we do not find a grid managed by the government. In these cases, local private generation units, denominated in this study Private Diesel Generator (PDG), assure the demand.

In Figure II.3 , we can see the relation between type of system and demand per capita. This graph shows that private generators and photovoltaic systems are applied only in low demand cases, being the DPP and DPP/Wind systems, which are connected to grid, the ones used for larger demands. We also see that DPP is commonly used to respond to a large spectrum of cases, which show that it is still the most flexible technology to adjust to different types of demand.

In terms of state of application from the 28 cases studied, we find that the majority (39.3%) is already applied, 25% is still being applied, and only 35.7% were not implemented yet.

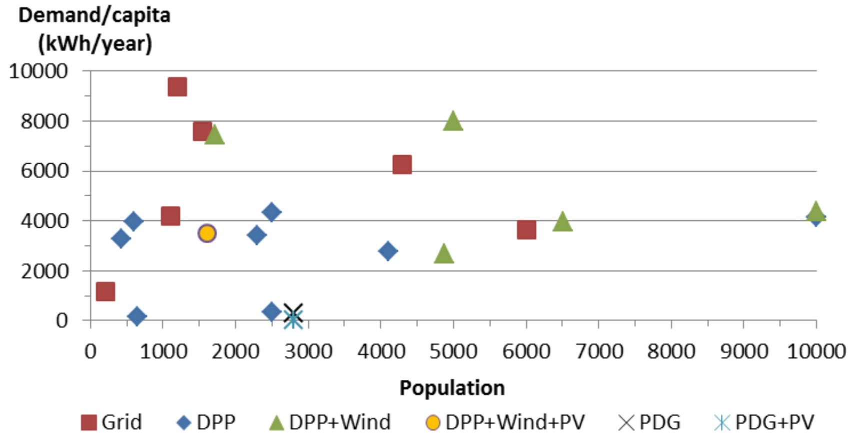

Figure II.3 - Distribution of existing supply systems by demand per capita and population bellow 10,000 people

Many of the projects that are only at the evaluation level are academic paper studies/thesis, to test a certain hypothesis, but there are also many examples of papers that explore the feasibility of a real economic investment, its risks and possible barriers. At an implementation level (applied or being applied), there are more studies regarding HRES design choices and in some cases after-analysis of implemented projects.

Another important detail is the fact that some of these projects refer to technology demonstrations. These projects focus on the integration of a certain renewable technology or storage system on a controlled environment, which does not necessarily represent the dynamics of the entire system or micro-community (e.g. Utsira, Norway [12] or Unst, Scotland [2]). Thus, the percentage of RES and the success of the technology integration in the global system may be overestimated. The number of long-term global analyses of islands is much smaller, but more interesting on a sustainable perspective, and from where we can learn more about islands dynamics.

As we look more closely in Figure II.4, to the percentage of renewable energy penetration on the total delivered energy (% RES), we can see that the values span from 0% to 100%, but most of the cases are in the range between 20% and 80%. We can see also that we have two cases of real implementation that achieve 100%: Samso, Denmark and Pellworm in Germany. Both cases are in Europe, connected to the mainland and with a small population (less than 5000 inhabitants). In both, there are large renewable power plants (wind in Samso, and photovoltaic and wind in Pellworm) that produce more energy than the total energy demand. Overall, the net balance is positive (the island produces more electricity than it needs) but when we look to a higher temporal resolution, it may happen that in some periods of the day the islands are consuming some power from the mainland that is not 100% renewable. So is fairer to call them net zero islands or net positive energy islands, than self-sustainable islands. However, from the presented case studies, only 29% are grid connected.

In Table II.4, we see the percentage of projects that used each resource (alone or combined). We can conclude that Photovoltaic is still a second option, after wind. The main reason for the choice for wind is due to its economic competitiveness with traditional fuel technologies. However, the evaluation of the cost-benefit analysis has to take into consideration the intermittence of the renewable resources. Thus, on a long-term perspective, it is necessary to account with daily and seasonal variability, and especially with its combination, regarding economic activities and structure of growth. Configurations with more than two renewable technologies tend to be residual - due to complexity of the system and more investment and operation costs.

Table II.4 - Number of projects that used each resource

Diesel	Wind	Photovoltaic	Biodiesel/biogas/biomass	Hydro	Wave	Grid
68%	86%	64%	21%	4%	4%	11%

In any case, the connection to other grid or diesel power plants have always to be available to assure the reliability of the grid, when the renewable resource is not available, but also to control the quality of the system. That is why in isolated systems, even if the resource is available, the diesel generation will always be partially on use and making it virtually impossible to go beyond 80%. The only way to avoid the use of diesel generation and achieving 100% is including storage in the system.

This fact proves the trend of studying and investing on renewable technologies for stand-alone systems like in islands, where the cost benefit analysis is usually positive for the renewables technologies. In any case, it is also interesting to notice that from all stand-alone cases (implemented or not) above 5000 people, HRES are not able to integrate more than 50% of renewable. Except for the case of El Hierro, with 10,000 inhabitants that expects to achieve 80% of penetration with the help of a hydro pump storage system. These HRES have necessarily to consider storage technologies, using normally batteries for low demands that are not economically viable on a large scale. We also can conclude that this percentage of RES is more dependent on the electricity end-use than on the total population.

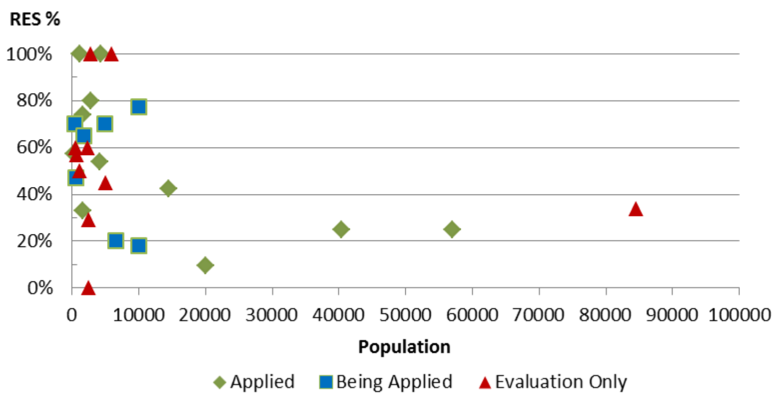

Figure II.4 - Distribution of projects by its application, renewable penetration and population

To tackle the difficulties around the implementation of storage systems (both technical and economic) we observe some sub-dimensioning of renewable systems in order to have reliable systems where diesel is the main energy source, leading in some cases to small RES penetration.

If we pay attention to the HRES configurations proposed for the different studies in Table II.3, we see that the combinations can be innumerous. Wind energy is almost a common denominator in these systems, being the DPP/Wind/Photovoltaic and DPP/Wind the more popular, with 28% and 14% of the cases, respectively. These combinations are the ones most used in the projects currently being applied.

In Figure II.5 we present the percentage of cases that consider storage technology (50%) by type of technology. The projects that do not use storage technologies and are stand-alone systems, do not achieve more than 25% of renewable penetration. We can see that batteries continue to have a major role on this type of systems, especially on the real applied cases, as batteries are able to provide energy in case of resource unavailability, but also contribute to supply quality control. On the other hand, pumped hydro can only be used if the geographical conditions allow for it (existence of water and altitude). We also observed some experimental case studies [20][52] using fuel cells with hydrogen, that are still not economically viable on a large scale. All the technologies are at least applied once (one case study with flywheel, three with batteries and one H_2 fuel cell).

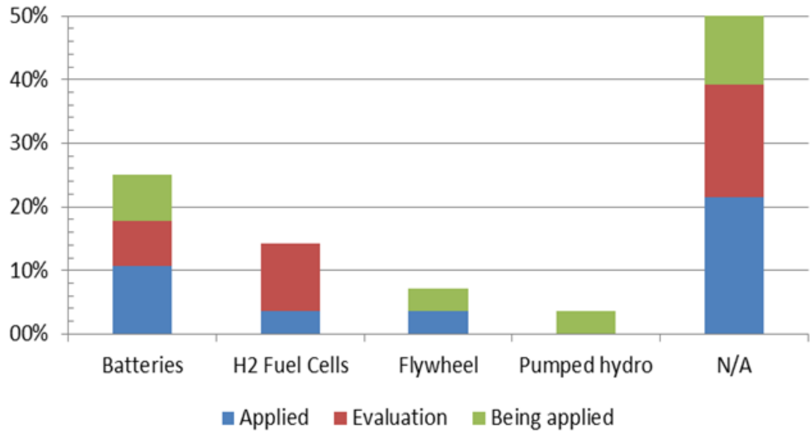

Figure II.5 - Storage technologies studied

Taking a more deep thought on the real role of electricity storage, we find that it can be quite diverse regarding the type of storage we want to achieve. For islands, we think that we need more complete storage systems, capable of storing renewable electricity from multiple hours to multiple days (like pumped hydro in El Hierro, Canary Islands, Spain, being applied). At the same time, power quality technologies (like flywheels) are still important to face the impact that renewables' intermittency causes on the grid. Systems with no storage availability (N/A) are the systems that are connect to the grid or do not present any information about it.

Regarding methodology of optimization of the projects, we see that only 39% of the case studies used some type of methodology or software. The use of methodologies has larger incidence on academic and experimental studies (70%) but few are used on real applied projects (18.2%). On case studies that are still being applied or already applied, we see in general that most use HOMER [53]. In projects that consider only evaluation, we observe a more diverse use of methodologies like RenewIslands [54], H2RES [20], TRNSYS [55], Simulink [56] or local surveys.

3.2 Remote villages

Another important set of isolated micro-communities is the case of remote villages. In general, they differ from the islands in the sense that, albeit they are isolated in terms of energy access, these communities are not completely geographically isolated and this has an impact in some of the variables that were analyzed for islands, such as the possibility of grid-connection.

In remote villages, it is very difficult to characterize demand due to the lack of systematic information about the community. Most communities are not connected to electric grid and when they are, the connection quality and service is very low. At the household level, they use biomass and/or kerosene for cooking, lighting and heating, which makes it difficult to quantify and then generalize energy demand values for the community. From these values, it is possible to make some kind of assumptions regarding electricity demand to design a system. Thus, in fact, we are characterizing electric demand by household (kWh/household) instead of community energy demand, being the community demand the cumulative consumption of the households (hh). This restricts openly the study to residential demand, once this type of isolated communities, normally, don't have any other energy consumption sector. This is a fairer indicator than demand per capita is, as we are able to compare directly specific energy needs. Table II.5 presents the overview, following the same type of indicators.

3.2.1 Remote village characterization

Looking to community energy demand on Table II.5 we see that it ranges from 1 to 55 MWh/year, except for the case of Lucingweni, in South Africa that present a value of 245.3 MWh/year. As we do not know the number of people living in each household, we can assume that there are significant differences in social and economic conditions that explain this discrepancy. For example, in a village with few hundred households, it is probable that some economic activity exists related to the support of village itself (e.g. small shops, schools, community centers). In general, we can observe that villages have less than 60 households and less than 50 MWh/year of demand.

Table II.5 - Remote villages' case studies comparative review

Remote village characterization								**Energy System characterization**						
Continent	**Name/ Country**	**Population** [hh]	**Economic activity**	**Grid**	**Demand** [kWh/hh/yr]	**Demand** [MWh/yr]	**Demand Growth Rate** [%/yr]	**Type of previous supply**	**RES** [%]	**Type of Supply**	**Storage**	**Methodology / Software**	**Application**	**Study**
Asia	Sheikh Abolhassan, Iran	10	subsistence	connected (since 2006)	5278	52.78	N/A	Grid	45%	Wind + PV + PDG (isolated)	batteries	HOMER	Evaluation only	[57]
Africa	North Garoua, Cameroon	19	subsistence	isolated	79- 365	1.3 - 6.9	N/A	N/A	60%	PV + LPG	batteries	HOMER	Evaluation only	[58]
Africa	Adar, Algeria	20	subsistence	isolated	1168	23.36	N/A	Diesel generators	100%	Wind + PV + PDG	batteries	HOMER	Evaluation only	[59]
South America	La Ciénaga , Argentina	23	subsistence	none	115	N/A	N/A	N/A	100%	PV (home systems)	batteries	N/A	Applied	[60]
Asia	Dinajpur district, Bangladesh	50	subsistence	isolated	365	18.25	N/A	N/A	43%	PV + PDG	batteries	HOMER	Evaluation only	[61]
Asia	Long Beruang, Malaysia	54	stone collecting	isolated	705.5	38.1	N/A	Private diesel generators (PDG)	100%	PV + PDG	batteries	N/A	Applied	[62]
Africa	Lucingweni, South Africa	112	subsistence	isolated	2190	245.3	6.00%	N/A	100%	Wind + PV	batteries	N/A	Applied	[63]

* We studied more cases than the ones presented here, but they were not consider for several reasons. One case was the one about the province of Jujuy in Argentine [64], a very remote region, where the houses where so dispersed that it did not make sense to consider them as part of the same community. Another case, is a successful implementation in Palestine [65] but we could not find enough system' quantitative data to compare with the other case studies. For the remote village of Rawdat Ben Habbas, on Saudi Arabia [66], we would only find energy demand in kWh/day/person, which did not allow us to compare with the other case-studies, where we don't find information about population but only for households. In conclusion, there is no systematized way to report the case studies, and it is very difficult sometimes to generalize and compare different indicators.

When we consider energy demand per household, as showed in Figure II.6, we see some changes. For South America, the values are very low (115 kWh/hh/year), while for Asia, we can find values between 365 and 705 kWh/hh/year, except in the case of Iran, with an extremely high value of 5278 kWh/hh/year (which can be explained by the heating demand in the cold climate with the proximity of mountains). In the case of Africa, values oscillate in a range of 79- 2200 kWh/hh/year. In conclusion, we are talking about a limit of 2200 kWh/hh/year for villages above 100 households and a limit of 1200 kWh/hh/year for villages under 100 households.

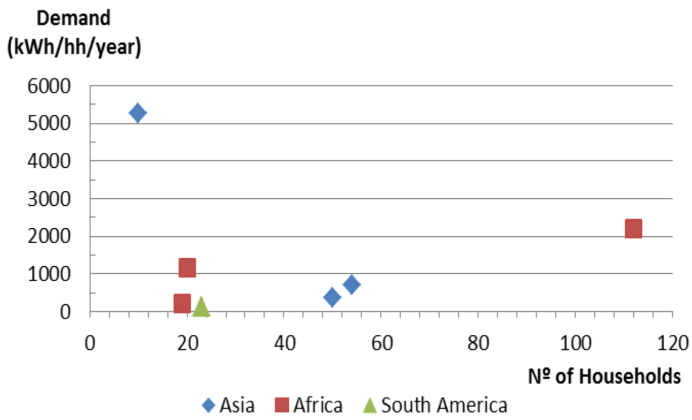

Figure II.6 - Yearly energy demand per household by geographical site

3.2.2 HRES characterization

Regarding the type of supply, we see that, except for one case study in Africa, all the cases are supplied by diesel. We also accounted that most of the remote villages studied are off-grid (86%), featuring only private devices. From all the cases analyzed, only one was (recently) grid connected.

Looking to the HRES solution for each case study, we see that 43% of projects were applied, which is consistent once again with the fact that in remote off-grid systems, the use of renewables can be cost-efficient.

On Figure II.7, we see 100% of the applied projects (3 out of 7 studied) have 100% renewable penetration. In these cases, apparently it is easier to meet the demand with pure renewable systems due to:

- Low demand and lack of a previous organized infrastructure of supply;
- Normally, these systems are only requested for few hours per day (usually evening hours for lighting);
- In these cases, the satisfaction on having electricity provided is very high.

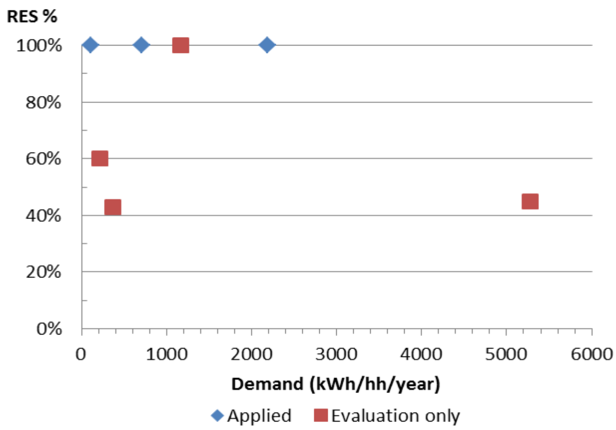

Figure II.7 - Percentage of renewable source on the hybrid renewable systems

On Figure II.8, we see that the most popular system on the applied cases is the photovoltaic/PDG configuration, with almost 30% preference, followed by the combination of photovoltaic systems with battery backup. On the evaluation cases, we see also that wind/photovoltaic/PDG accounts for 30% of the cases and is proposed as a potential alternative to photovoltaic-only systems. In these cases, the diesel works in general as second backup supplier in extreme cases, as they are not part of the community electric system. Every other system considers batteries as storage technology, which, for small demands, is enough.

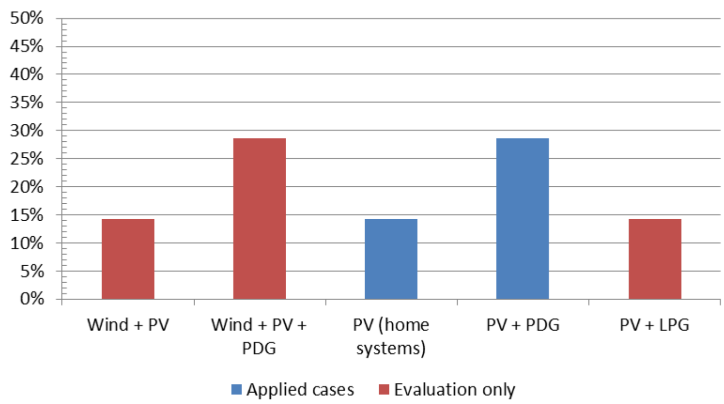

Figure II.8 - Percentage of use of each type of hybrid system, on the analyzed case studies

Regarding the use of methodology to optimize the system design, we found that 50% of the projects used HOMER [53] as design software. Interestingly, it was used only on projects that were evaluation cases - this demonstrates the adequacy and applicability of this software to this scale and type of communities, with increasing use in recent years. Thus, we can concluded that the current practice does not follow yet any methodological approach based on energy systems modeling and optimization.

3.2.3 Islands versus Remote villages

Having presented an analysis for these two types of micro-communities, we can find some differences that are highlighted on Table II.6.

Table II.6 - Comparison of main between Islands and Remote villages

	Islands	Remote Villages
Main activities	Fishing, farming, agriculture Tourism	Subsistence
Demand dimension	Differs greatly with geographical site [111-754000] MWh/year Higher peak demand - 24 hour needs	[1.3-245.3] MWh/year Mostly requested only on evening hours
Grid connections	71% isolated – very costly or impossible to become connected to mainland grid	86% Isolated – possibility of becoming connected to the grid
Major hybrid system configuration	Wind/Photovoltaic/Diesel Power Plant	Photovoltaic/Private Diesel Generator/batteries
Major backup system	Diesel power plant (existing supplier & sub dimensioning of renewable systems) – more reliable	Batteries
Renewable penetration	Up to 80% for yearly demands lower than 20,000MWh	Up to 100% for yearly demands lower than 2,000 kWh/household
Economic overview	Public/cooperation investment (South) vs Private investment (North) Costly isolated backup technologies combined with renewable intermittency Sustainable in long term analysis	
Social overview	More system success with population integration in the process of decision and caring [65] Night lighting in remote villages improve educational and social level [64][67][68]	

The maximum demand on remote village (245.3 MWh/year) is near minimum demand on the island's case (111 MWh/year), and the maximum differs in two orders of magnitude. The main differences are on dimension and main activities, since normally on islands there is some use of natural resources (sea, fields, etc.) that will influence the electric demand. In islands, we must account also with tourism, which implies that system's design meet seasonal oscillations. This brings us a level of commitment between a reliable backup able to respond to peak demand (that normally is diesel), and a good percentage of renewable source able to ensure normal demand over the year. In Islands, differences between geographical sites are more representative, and are related to the community activities and regional socio-economic development. In remote locations, we note higher percentages of renewable penetration due to the small size of the systems that must rely on batteries for backup and storage, and also to smaller range of working hours (evening).

In terms of grid-connection, there is a dominant difference, which is the possibility of remote villages to become grid connected (like happened with the case study of Sheikh Abolhassan, Iran). Normally that possibility is not viable on isolated islands, leading to an extra need for an accurate dimensioning of the hybrid systems, taking in account projections on growth rates, since these type of systems normally represent big investments for decades.

We note that the preferable HRES configurations are different. In islands, we have innumerous possible configurations due to dimension and heterogeneity of islands and renewable resource, but the abundance of wind resource on sea locations makes the majority Wind/Photovoltaic/DPP. In remote villages, systems oscillate between photovoltaic and diesel technologies since normally there is good solar resource and few reliable information of other resources, although some systems are starting to be complemented by micro wind turbines.

Renewable percentages of the hybrid renewable system demonstrate to be higher in remote villages (100% from photovoltaic combined with batteries) once electricity demand is very low and normally there was no electricity supplier before, leading to an initial period with no increasing demand and high satisfaction with the system. For these cases, we could not find demand growth values, but the experience from the installation of these projects says that after a while and in order to improve their welfare, communities tend to buy more appliances for which the system was not dimension [69]. This fact takes to additional wear of the batteries, shorting the life cycle of theses HRES.

In islands, we see a large range of renewable percentage on the applied cases: from 9% to 80% on stand-alone systems, and 25% to 100% on grid-connected systems. On the first cases, we notice that it is difficult to rely only on renewable source and storage systems. In bigger system's dimension, only pumped hydro is reliable enough to give security of supply, and achieve high percentages of renewable (see the case of El Hierro, on Canary Islands, that currently is being applied). However, pump hydro isn't a viable technology everywhere, per example, if access to potable water is a problem or if there is not a geographical slope. For that stand-alone cases we see that previous conventional energy supply systems, are predominant on the design of the new hybrid system, working as complementary backup and peak demand response, with the renewable technologies assuring a part of the demand over the year (but also with small percentages). Regarding grid-connected systems, we see that they achieve more easily 100% RES, since the local renewable production is higher than the local demand and they are connected on a larger national grid capable of absorbing and manage all these suppliers (see the case of Samso or Pellworm).

In terms of financial investment, we encounter some differences by region. In Northern islands, where normally green electricity and renewables are a culture and a pride, there is a tendency to have private investment (by users, municipalities or even some enterprises) on these hybrid systems, rather than a governmental/state investment. Grid connectivity can be a reason, making these projects less complex and costly than the ones standing alone. This contrasts with what happens in the Southern islands where HRES are normally financed by the national state or governments' cooperation's.

In some cases, the integration of renewables was reported together with the increased cost of energy, mostly for backup technologies (excluding diesel generators). This difference is only highlighted since the energy cost of conventional energy many times does not internalize transportation's cost (in remote communities this is usually high) or environmental costs (e.g. associate CO_2 emissions taxes). This is also the reason why there are some international programs of cooperation, which assure that all parts of the agreement are doing an effort for the world environment and climate change.

On a social level, from what we could access, HRES are more successful when integrate the population in the process of discussion, decision and implementation than when it is an "outside" decision without choice. In remote villages in particular, we also find a major contribute of night lighting to improve people lifestyle and wealth development, allowing to do school's homework (improving education) and to use sociability spaces between the community, especially to women, outside their personal space. The social opportunity that HRES bring, can help meeting some of the millennium goals for development

[70], like helping to achieve universal primary education, promote gender equality and empowerment of women, ensure environment sustainability or even help to develop global partnerships.

3.3 Reporting framework for HRES projects

Based on the analysis of the different hybrid renewable energy systems and considering the difficulties to systematize information from the different projects, we suggest the works on the design, analysis and implementation of this type of system use the following framework to report the data:

- **Regarding electric/energy demand**: hourly, weekly, monthly and yearly demand profiles; off-peak and peak load (to account season oscillations); description of the energy use activities by economic activities and general economic growth rate; population size, population growth rate, number of households; any special feature that may influence significantly the energy demand (such as the existence of a special facility like a manufacturing plant or a hotel resort);
- **Regarding the energy system technical details**: design of the current supply system, including power of the generation plants; renewable resources availability and variability (daily, monthly); technical details about the generation and storage solutions (manufacturer, efficiency, power, etc.)

These factors are determinant to the design of a HRES, not only in terms of reliability and robustness, as well as in terms of percentage of renewable penetration, but also in terms of match between demand and supply. In this way, the comparison and benchmarking among the different projects can only be achieved if the reported data accounts for all these variables.

4 Conclusions

With this review, we can conclude that the interest for hybrid renewable energy systems is increasing in the world, as a way to provide sustainable energy independence for small communities.

The more common configuration of hybrid systems in islands is wind/photovoltaic/DPP (among many other possible configurations) and in remote villages, photovoltaic/PDG coupled with batteries (few possible configurations).

Storage technologies continue to be a challenge for islands in terms of efficiency and economics. In most cases are not viable with the present state of the art, especially for large scale hybrid systems with different energy suppliers, where the most appropriate option is pumped hydro that depends on the existing geographical conditions. Until storage technology evolves for large systems, it will be difficult to go over 50% of renewable penetration on HRES. In remote villages, batteries are currently a good technical and economical choice.

We denote also an increase on the use of methodologies to design the energy systems of isolated micro-communities. The methodologies are still more applied on the case of remote villages, where they demonstrated more accuracy (system's scale is smaller than in islands). These methodologies have been generalized to island case studies in the more recent years, especially for islands smaller than 10,000 people. In bigger islands, with different main economic activities starts to be difficult to manage all the demand patterns.

Definitely, improvements for HRES in isolated islands go for:

- more accurate study of demand estimation, and multiple renewable resource dynamics and variability on the hybrid system's design, aiming to security of supply;
- more reliable storage systems, decreasing progressively the use of conventional energy suppliers (like fuel) and taking in account the type of storage role we need (multiple day or daily storage, power quality, etc.) adapting the type of technology and design of the system;
- use methodology tools to optimize the systems, encompassing four main vectors: island economic structure (and so demand), renewable resource estimation, adequacy of storage technologies, and real investments projection;
- considering public economic investment in these systems as a necessary effort as developer of economic and educational level and welfare, approaching these communities from self-sustainability;
- and, of course, the success of these systems would have to bring the population closer to the project's decision and implementation.

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Chapter III
Modeling the impact of integrating solar thermal systems and heat pumps for domestic hot water in electric systems – The case study of Corvo Island

Abstract

The use of solar thermal systems with electricity backup and heat pumps as hot water suppliers in residential buildings seems to be a very promising way to increase energy efficiency. Nevertheless, the massive adoption of such solutions in small networks (neighborhood, village) may induce problems in the electric grid management. This study explores the impact of such systems in small electric grids, using an hourly electricity backup load model. To test and validate the model, we used the island of Corvo (Azores), a small isolated community where it is being implemented a project of electrification of domestic hot water systems. We consider different load scenarios to manage the backup of DHW systems and analyze its consequences on the peak load and overall energy demand. For Corvo, for the best case where the backup is limited and distributed along off-peak hours, we observed an increase of 24% in the peak load and 7.5% in the annual energy demand. Critical values of peak load are found in winter, when daily solar irradiation is lower than 2000 Wh/m^2/day. We conclude that the solar thermal systems are responsible for most of the peak load increase, but since they have the flexibility to adjust the electric backup hours due to the thermal storage capacity, the use of these systems can minimize the impact on the grid. Heat pumps on the other hand, albeit being more efficient in terms electric backup, are less flexible to contribute to the grid management as they operate continuously.

Keywords

Domestic hot water; Solar thermal; Heat pumps; Renewable energy; Isolated micro-communities; Hybrid renewable energy systems

1 Introduction

The access to energy fuels in isolated and remote communities, even in developed countries, is often expensive and unreliable for the local population [1]. The use of local endogenous resources is the best approach to tackle this challenge. Thus, some remote communities like islands, are developing projects of hybrid renewable energy systems to generate electricity and also domestic hot water [2][3][4].

This is also the case of Corvo Island, the smallest (17 km^2) and most Western Island of the Portuguese Azores archipelago in the mid-Atlantic ocean, with 430 inhabitants living in 144 houses [5]. In Corvo, all energy sources are imported (diesel for electricity generation and liquefied petroleum gas (LPG) for domestic hot water and cooking). This poses several challenges to the community. Economically, this solution is not sustainable and the regional Government of Azores has to support the fuel transportation by ship through subsidies. In terms of security of supply, winter storms do not allow ships to harbor or small aircraft to land in the island, and is common to have temporarily failures in the supply of energy and other goods. Further, the government has to subsidize the transportation of fuels, which represents a significant economic burden. This has been particularly dramatic in the case of domestic hot water and cooking, whose energy has been provided by LPG over the last years.

All over the world, the use of solar thermal systems and heat pumps for domestic hot water has been increasing over the last years, as a way to increase the energy efficiency in the residential sector [6]. As Corvo Island struggles with external dependence due to its remoteness and despite the expected increase of electricity generation, to use renewable technologies for DHW generation seems to be the right option, both economically, socially and environmentally, as currently the electricity is exclusively provided using diesel generation. It is expectable that the electrification of the DHW creates enough electricity demand that enables the diesel generation to operate more efficiently in off-peak periods, but also to make economically viable the installation of a wind park and thus induce a decarbonization of the electricity generation.

In order to replace the gas water heaters while reducing users' energy bill, the municipality, with the support of the regional government, is promoting the installation of residential DHW systems in every house, choosing to implement solar thermal collectors (ST) and heat pumps (HP). As the government idea is to phase out completely the LPG use over the next years, the government decided that the backup solution for ST would be electric, instead of using the existing gas DHW systems for backup. The main reason to consider the use of heat pumps was mainly because in some of the houses there was not enough roof area to install solar thermal systems.

Solar thermal collectors are a renewable energy technology used for DHW needs for the last two decades, in Southern European Countries [7] and United States [8]. On the other hand, heat pumps are increasing its share as technology for DHW, as they are extremely efficient and can easily be coupled with renewable electricity, as photovoltaic [6] or wind [9]. However, the massive adoption of such solutions in a small network (neighborhood, village) has to take in account possible problems in the electric grid management [1].

Since the beginning of 2013, 38 houses in Corvo have already these systems in place and the remaining ST and HP systems will be installed in the rest of the houses until mid-2014.

As ST and HP systems use electricity as backup and main energy supplier respectively, it is expectable a significant impact on the electricity demand, especially in winter periods when there is less solar radiation. The risk that the current generation system might not be able to respond to the demand increase in extreme winter situations is real.

This study estimates the impact on the electric grid of the replacement of DHW appliances, by presenting an hourly-based model of the ST and HP systems. The results were validated using the electricity demand data from 2013, and later were analyzed testing a set of different scenarios that consider different water use profiles and backup use strategies.

The paper proceeds as follow: Section 2 describes Corvo's energy system, Section 3 introduces the hourly models for ST and HP and in Section 4 we present Corvo DHW model, concluding in Section 5.

2 Corvo energy system

Corvo is the smallest island in the Azores' archipelago in the middle of the Atlantic Ocean, with 430 inhabitants and 144 houses [5]. Due to its small size and insularity, energy demand in Corvo Island is quite particular, when compared to other islands with the same amount of population [10]. Nowadays, a single diesel power plant with four generators (totaling 536 kW of installed capacity) supplies electricity to the island. As shown in Table III.1, the annual energy demand is 1377 MWh/year, the peak power is around 225 kW and the average unitary cost of production is 223 €/MWh [11]. Until 2012, thermal energy was supplied by butane gas with an annual consumption of 3315 butane gas bottles, 60% of which, according to [12], is used for domestic hot water, which results in a value of 335 MWh/year. The government expenses regarding the transportation of gas to the island correspond to 22.2 € per bottle of LPG. Table III.1summarizes the current energy loads and costs for electricity and DHW production.

Table III.1 - Costs of operation in current situation

Government costs	Load	Operation costs		Total cost
	[MWh/year]	Unitary cost	Total per year	[€]
Diesel Power plant	1377.8	223 €/MWh	307 249 €	351404
DHW Butane Gas demand	335	22.2 €/bottle	44 155 €	

The idea of replacement of butane gas as hot water supplier (at residential level) has been into consideration by the regional government of Azores and the municipality, since 2008. However, many technical, social and economic hurdles had to be overcome: on one hand, there was some skepticism on the capacity of solar thermal systems to respond to all the demand even on severe winter days. On the other hand, some concerns on the security of electricity supply by the local distributor, that had to be sure that all the installed power generation capacity was available, and with whom the authors have been working closely on this topic over the last couple of years and that resulted in the work presented in this paper. After all the issues were answered, in the beginning of 2013, the municipality and regional government started the implementation of the final project, consisting in replacing the butane gas systems for domestic hot water production in every house by solar thermal collectors or heat pumps (when the roof area and orientation is not enough or adequate, or there is no space outside the house to place the solar system). In 2011, a detailed survey was made for every house, describing the typology of the house, occupancy, previous and projected DHW system, and the type of hot water tank that could be installed. Table III.2 presents a summary of all the 144 systems that are projected. At the time this paper was written, 38 houses had already new DHW systems implemented (27 ST and 11 HP).

Table III.2 - DHW projected systems for the 144 houses of Corvo Island

DHW Systems		**Power**	**Number**	**Total**	**Total Power**
		[kW/system]		[%]	[kW]
Solar thermal collectors (ST)	Thermosyphon & Forced circulation	2.30	66	46	152.0
Heat pumps (HP)	Heat Pump	1.86	78	54	144.8

2.1 Domestic hot water demand

According to an island survey on the energy consumption habits [13], and the Portuguese thermal regulation for buildings (RCCTE) [14], we considered that the DHW demand in Corvo is the one described in Table III.3. This is in accordance to the literature - in [15], daily DHW demand is estimated to the between 30 (low), 50 (medium), 60 (high) l/day/person.

Table III.3 - DHW demand in Corvo

Daily average per person	**Average persons per house**	**Daily consumption per house**
[l/day]	[number]	[l/day/house]
40	3	120

Although we can consider that the DHW daily demand is constant per person, we know that the consumption in each house differs from hour to hour. According to [16] and [17], there are two peaks of demand, one in the morning and one in the evening, which correspond in general. There is also some demand between peaks.

The analysis of the activities of each group of users determines the usage pattern and the time when the highest DHW peak occur. In order to build an hourly consumer profile adjusted to the total daily demand, we assumed three groups of consumers presented in Table III.4: one with predominant demand in the morning (“Morning”), one with the predominant demand in the evening (“Evening”), and one distributed throughout the day (“Distributed”).

In general, when we talk about systems with storage tanks, it is assumed that the hourly variations may be negligible, so most reports consider the daily or monthly energy needs. This is the case of *Solterm 5.1* [18] - the software for dimensioning solar thermal systems according to Portuguese regulation [14]. However, in terms of the electric system operation, it is very important to understand the exact period of the day when the backup power of ST or HP occurs.

Table III.4 - Assumed profiles of DHW in Corvo Island

	Morning [l]	Evening [l]	Distributed [l]
0h-8h	0	0	0
8h-9h	40	0	0
9h-10h	40	20	20
13h-14h	0	0	20
19h-20h	0	40	0
20h-21h	40	40	40
21h-22h	0	20	40
22h- 24h	0	0	0

2.2 Electric load

We accessed the hourly electric load data for Corvo, from 2010 to 2013, provided by the Azorean Electric Company (EDA), and chose to use the 2012 load as base load, since it is a representative load prior to the installation of DHW systems.

Figure III.1 presents the load profile for a week of October in 2012. It is interesting to see that there are not any substantial differences on peak load between weekdays and weekends. This can be explained by the absence of industry in the island or the existence of few service buildings. As people work and live in the same village, they go home often during the day, even to have lunch. There are still two peaks, one in the morning (around 11h-12h, lower) and one at night (around 20h-22h, higher), and the only difference from weekdays to weekend days is the delay in morning peak that, at weekends, tends to occur later (around midday).

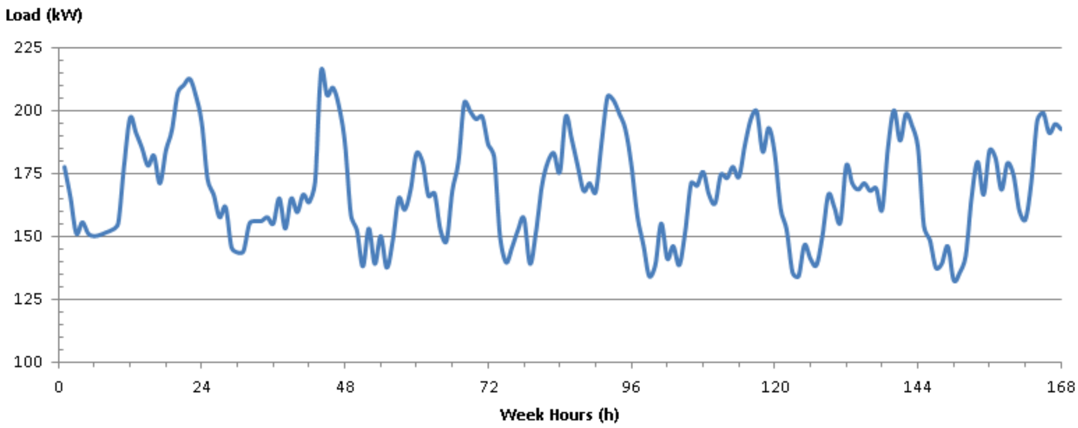

Figure III.1 - Corvo electric load for week 43 (October) from Saturday to Friday

In Figure III.2, we represent the evolution of electricity consumption on residential sector (47% of total electricity demand) between January 2011 and May 2013 for every island in the Azores archipelago. We see that in every island, there was a substantial decrease on electricity demand (between 4% and 9%) between 2011 and 2012 due to economic crisis, especially on larger islands like São Miguel or Terceira. In 2013, we see that in every island there is an increase again of the domestic consumption.

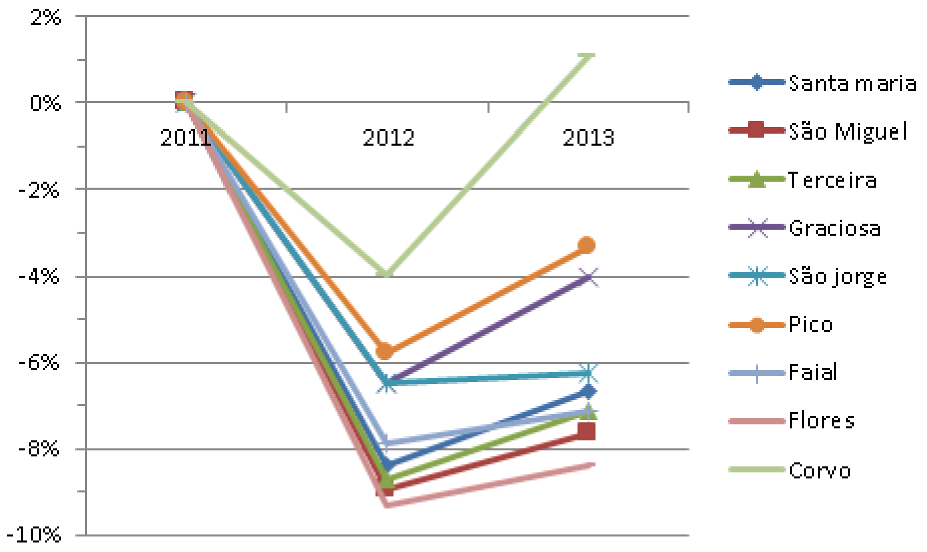

Figure III.2 - Evolution of electricity demand on residential sector on Azores islands, to the same period (January-May)[11]

It is interesting to see that Corvo Island presents for 2013 the highest increase, around 5%, surpassing the 2011 values. This fact suggests that there is a special event in 2013 in Corvo that induced this larger increase, for example the introduction of the new DHW systems and consequent electric backup.

2.3 Solar radiation data

For the solar radiation data, we use the climate database of NASA [19] to evaluated the hourly global irradiance on horizontal plane and the data base of the software *Solterm 5.1* [18] for the yearly estimated hourly values for water net temperature and ambient temperature (Figure III.3). In Figure III.4 is the daily global irradiation on the optimal inclination and azimuth to implement the solar panels in Corvo [inclination 30º, azimuth 0º (South)].

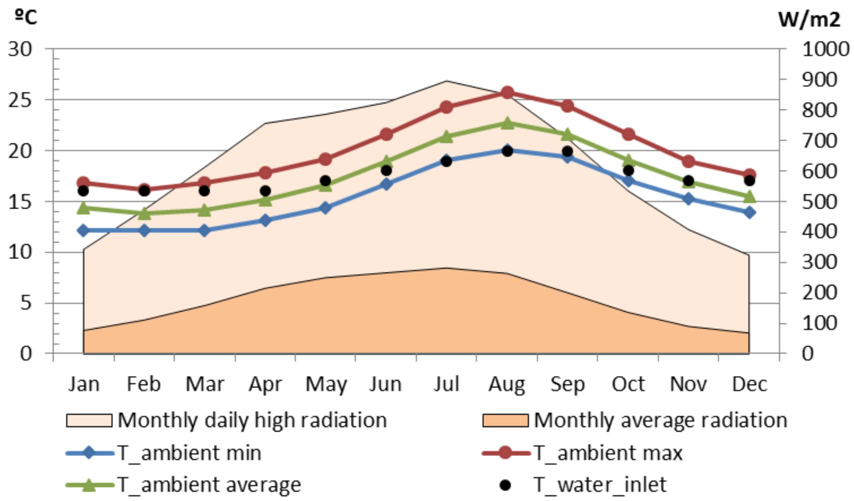

Figure III.3 - Monthly horizontal global radiation on Corvo Island, and ambient and water inlet temperatures

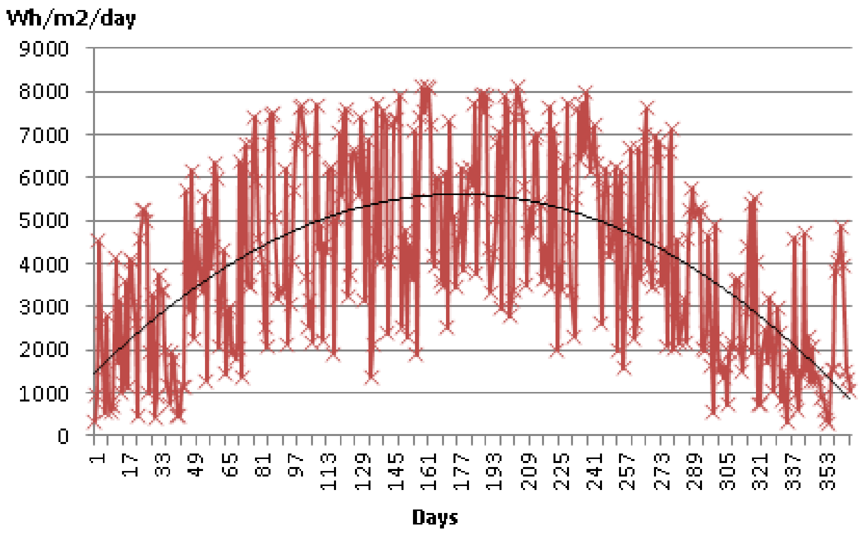

Figure III.4 - Daily global Irradiation on 30º inclined plane in Corvo Island

3 Modeling DHW

In this section, we describe the hourly model of DHW systems for solar thermal technologies and heat pumps proposed to determine the additional electric load introduce by these systems, proposed in this paper.

3.1 Solar thermal model

Using the incident global radiation data, we can calculate the energy produced by the solar collector for each hour of the year $Q_{\mathrm{solar}}(\mathrm{t})$ with Equation III.1:

$$Q_{solar}(\mathrm{t}) = \frac{A_{abs}}{1000}.(\mathrm{I_{col}}(t).\eta_{\mathrm{col}}\text{-}(\frac{\mathrm{U_c}.(\mathrm{T_m}(t)\text{-}\mathrm{T_{amb}}(\mathrm{t}))+\varepsilon.\sigma.(\mathrm{T_m}(t)^4\text{-}\mathrm{T_{inlet}}(t)^4)}{8760}); \quad Q_{solar}(\mathrm{t}) \geq 0 \ \ [\mathrm{kW/h}] \qquad \text{(III:1)}$$

where:

- A_{abs} is the area of the flat-plate collector [m^2],
- $\mathrm{I_{col}}(t)$ is the hourly solar irradiation on the collector plane in $\mathrm{W/m^2}$,
- η_{col} is the collector efficiency [%],
- $\mathrm{U_c}$ is the conductive loss' coefficient [$\mathrm{W/K.m^2}$],
- ε is the emittance [%],
- σ is the Stefan-Boltzmann constant [$\mathrm{W/K^4.m^2}$],
- $\mathrm{T_{amb}}(t)$ is the hourly ambient temperature [K],
- $\mathrm{T_{inlet}}(t)$ is the hourly inlet water temperature on collector in [K] and,
- $\mathrm{T_m}(t)$ is the hourly average temperature defined by Equation III.2:

$$\mathrm{T_m}(t) = \frac{\mathrm{T}_{max}+\mathrm{T_{inlet}}(t)}{2} \ [K] \qquad \text{(III.2)}$$

To determine the hourly hot water thermal energy needs we use Equation III.3:

$$\mathrm{Q}_{DHW}(t) = \frac{C_{p\ water}.\rho_{water}.V_{DHW}(t).(\mathrm{T_{max}}-\mathrm{T_{inlet}})}{1000.3600} \ [kW/h] \qquad \text{(III.3)}$$

where $C_{p\ water}$ is the specific water heat (4.186 KJ/kg.K), ρ_{water} is the water density (1000 kg/m^3) and V_{DHW} is the volume of hot water demand, in liters, at each hour t.

Having as inputs Q_{solar} and Q_{DHW}, we can calculate the energy stored in the water tank at hour t using Equation III.4:

$$Q_{Tank}(t) = Q_{Tank}(t\text{-}1) + Q_{solar}(\mathrm{t}) - \mathrm{Q}_{DHW}(t)\ ; 0 \leq Q_{Tank}(t) \leq Q_{Tank}\ max\ [kW/h] \qquad \text{(III.4)}$$

where Q_{Tank}max is the maximum capacity of storage tank.

Finally, we can calculate the energy needed for electric backup, when the solar system is not enough to fulfill the demand. Efficiency of the electric backup is considered to be 100%, so we calculate Q_{backup} through Equation III.5.

$$Q_{backup}(t) = \mathrm{Q}_{DHW}(t) - Q_{solar}(t) - Q_{Tank}(t\text{-}1)\ ;\ 0 \leq Q_{backup}(t) \leq P_{nom}\ [kW/h] \qquad \text{(III.5)}$$

where P_{nom} is the nominal power of the resistance in the tank.

3.1.1 Losses

In order to evaluate the impact that thermal losses on the hot water tanks can have on the electric grid, we considered losses in this model. The objective is to determine the relative weight of losses compared to the hot water use in the electric backup to maintain the water in constant temperature of 60 ºC, and not to study in detail the stratification inside the tank. We used a simplified approach to account for thermal losses on the storage tank, as a whole, which is described by Equation III.6:

$$Q_{loss}(t) = \frac{U_{loss} \cdot (T_{max} - T_{amb}(t))}{1000} \; [kW/h] \tag{III.6}$$

We use T_{amb} since we consider the solar system to be outside the house, next do the solar collectors, but inside temperature can be also be used for systems where the tank is placed inside the household.

In this case, Equation III.4 is replaced by Equation III.7:

$$Q_{Tank}(t) = Q_{Tank}(t\text{-}1) + Q_{solar}(\mathrm{t}) - Q_{DHW}(t) - Q_{loss}(t)\,;\, 0 \le Q_{Tank}(t) \le Q_{Tank}\, max \; [kW/h] \tag{III.7}$$

The calculus of Equation III.5 is the same but now with the new $Q_{Tank}(t)$ found Equation III.7.

3.1.2 Off-peak backup

It is normal to install ST systems with clock switches on the electric backup power system, in order to take advantage of the off-peak tariffs when available. In this case, we need to limit the use of backup to the period where the switch is on. To assure that the system responds to daily DHW needs, we assume that backup will only heat the volume of daily DHW consumption. In this case, the calculus of $Q_{backup}(t)$ is given by Equation III.8:

$$\begin{array}{c} for\ t = [offpeak\ hours] \\ \text{if} \;\; Q_{Tank}(t\text{-}1) < Q_{DHW\ daily} \rightarrow Q_{backup}(t) = Q_{DHW\ daily} - Q_{Tank}(t\text{-}1) \; [kW/h] \\ if \;\; Q_{Tank}(t\text{-}1) > Q_{DHW\ daily} \rightarrow Q_{backup}(t) = 0 \\ for\ t = [peak\ hours] \rightarrow Q_{backup}(t) = 0 \end{array} \tag{III.8}$$

3.2 Heat pumps model

From the various types of heat pumps systems for DHW, the one considered here is the air-water heat pump for domestic hot water purposes. The heat pump is powered by the electric grid and extract the heat contained in the air, heating the water in the tank.

The electricity needed by the heat pump to heat the water in the tank is given by:

$$W_{HP}(t) = \frac{Q_{HP}(t)}{COP} \; [kW/h] \tag{III.9}$$

where:

- *COP* is the Coefficient of Performance of the heat pump and,

- $Q_{HP}(t)$ is the thermal energy needed by the heat pump, that is given by Equation III.10

$$Q_{HP}(t) = \left(Q_{Tank}\ max - Q_{tank}(t\text{-}1)\right);\ 0 \leq Q_{HP}(t) \leq\ P_{nom}[kW/h] \tag{III.10}$$

where $Q_{Tank}(t)$ is calculated by Equation III.11:

$$Q_{Tank}(t) = Q_{Tank}(t\text{-}1) + Q_{HP}(t) - \mathrm{Q}_{DHW}(t)\ ;\ 0 \leq Q_{Tank}(t) \leq Q_{Tank}\ max\ [kW/h] \tag{III.11}$$

In this model, we do not impose hour limits on the electric backup, since this is an appliance that works on a continuous cycle. Also, as we consider the heat pumps to be inside the houses, we assume that there are the losses on the storage tanks can be neglected. Otherwise, the use of Equation III.6 and including this term in Equation III.11 is still valid.

4 Corvo DHW modeling

In this section, we first validate the model derived in the previous section for Corvo Island and then we use it to test different scenarios and study its impact on the electric grid.

4.1 Model parameters for Corvo's systems

For Corvo, we consider that the solar thermal technology is a thermosyphon system with flat-plate collectors (where the area of absorption is equal to the collector's area), the use of an exterior storage tank and we assume a standard efficiency of 80%. The collector's area and storage tank were determined to be able to fulfill the demand of three persons per system, consuming 40 l/day/person, at 60ºC. The values presented in Table III.5 were used in Equation III.1. Figure III.5 represents schematically an individual system of solar thermal collectors and hot water tank, like the ones installed in each house of Corvo.

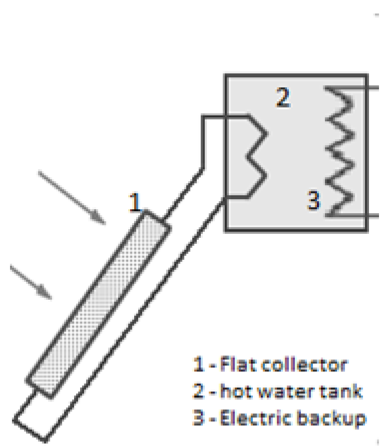

Figure III.5 - Individual Solar thermal collector scheme

Table III.5 - Solar system relevant parameters [18]

Solar Collector				Storage Tank	
Area [m²]	η [%]	ε [%]	Fluid	Volume [l]	U_c [W/m².K]
4.2	80	80	Water	200	1.8

We also considered $T_{max} = 333K$ (Equation III.2) [14], Q_{Tank} max $= 10.46\ kW$ (Equation III.4) due to the size of the storage tank (corresponding to 200 l), and maximum backup power per hour $P_{nom} = 2.3\ kW$ (Equation III.5). For the model with losses in the tanks, we used $U_{loss} = 2.7\ W/K$ (Equation III.6). When limiting the backup to the off-peak hours, we considered the off-peak period to be from 0h to 8h (Equation III.8), while $Q_{DHW\ daily} = 6.138\ kW$, which corresponds to 120 l of hot water demand.

For the heat pump model, we used the parameters presented in Table III.6, which were use in the calculus of Equation III.9 and Equation III.10, where Q_{Tank} max $= 10.465\ kW$ (Equation III.11). Figure III.6 represents schematically the individual heat pump system.

Table III.6 - Heat Pump relevant parameters [6]

Heat Pump		Storage Tank
COP	Power [kW]	Volume [l]
2.5	1.86	200

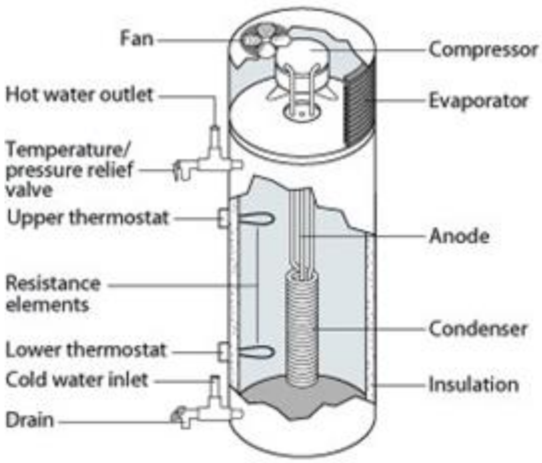

Figure III.6 - Heat Pump air-water [8]

4.2 Comparison of solar thermal systems and heat pumps

Before validating the overall model, we first discretize the two technology profiles and its hourly demand profiles for the totality of the houses (144) in Corvo, to see the differences.

For solar thermal collectors, we see in Figure III.7 that for winter days with less than 1200 Wh/m² daily irradiation (an average of 200 W/m² over 6 hours), there will be high peaks of backup (around 475 kW) in the morning and in the evening. The peak in the morning will be especially higher if in the previous day there was not enough radiation and there is no thermal energy stored in the water tanks. For example, we see that in the 3rd day of the week, we had a morning peak, but then the daily solar irradiation was able to store enough thermal energy in the tanks, and there was no need for backup in the evening.

If daily solar irradiation goes above 2000 Wh/m²/day (an average of more than 300 W/m² over 6 hours) for at least one day, the solar system is capable of covering the DHW demand, as we see in Figure III.7 and Figure III.8, and that's the reason why in summer the model doesn't present any electric backup.

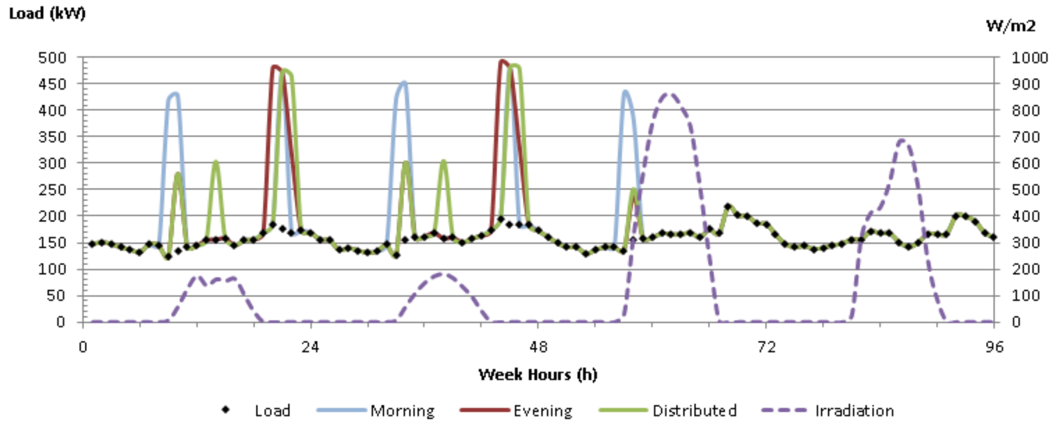

Figure III.7 - Comparison of different hourly demand profiles for ST collectors model, on four days of Week 7 (winter)

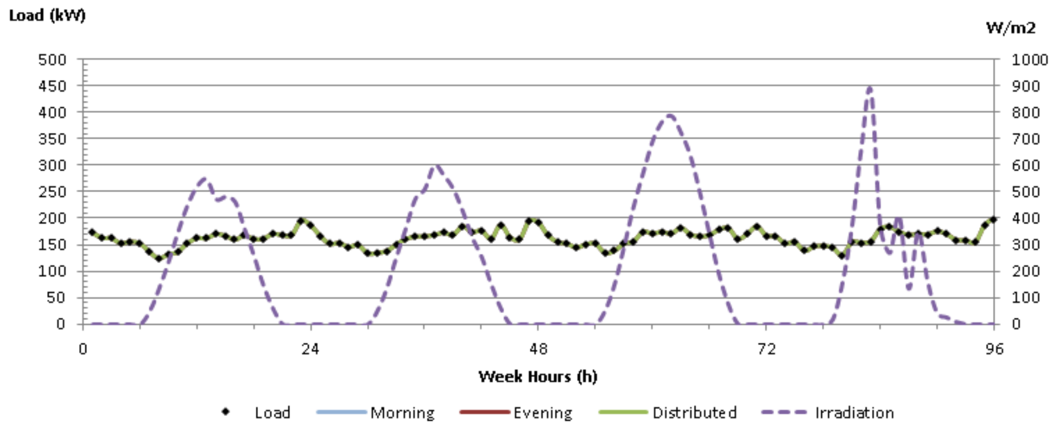

Figure III.8 - Comparison of different hourly demand profiles for ST collectors model, on Week 26 (summer)

For heat pumps, we see in Figure III.9 that the electric needs are proportional to the hourly DHW demand, which is the reason why we observe a load cycle along the year. The HP peak loads are much lower than the solar thermal, since we consider that heat pumps have a COP of 2.5, making the electric backup more efficient. The evening peak is naturally higher once the heat pump is working at the same hour of the normal peak load.

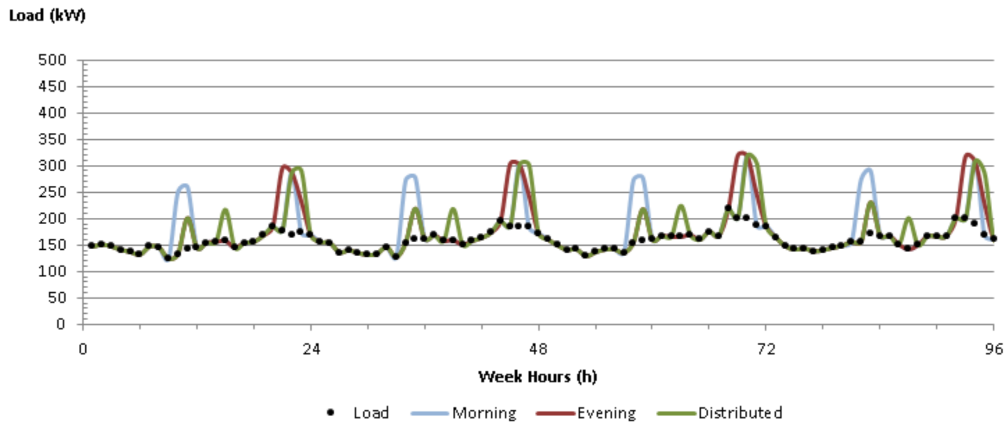

Figure III.9 - Comparison of different hourly demand profiles for HP model, on four days of Week 7 (winter)

From the previous figures, we can conclude that during winter, ST will have more impact on the peak load due to low irradiation, while heat pumps have a constant load impact that will have a more predominant weight on the overall model on summer, when ST is fully supplied by solar energy.

Table III.7 presents a comparison between the current energy system demand and costs and two scenarios: one with 100% ST and another with 100% HP. In terms of annual energy demand, installing ST systems in 100% of the houses would have an impact of only 1.4% increase in terms of electricity consumption, but in terms of peak load of the worst day in winter, it would represent an increase of 112%. This would be drastic and might cause too much stress for the actual diesel power plant. On the other hand, if we installed heat pumps in 100% of the houses we would have an increase of 9% in the annual energy demand, and 46% in the peak load, which, compared with the 100% ST scenario, would be more reasonable.

In terms of costs, any of the two scenarios (ST or HP) would introduce savings on the operation of delivering electricity and DHW to the end-users. As primary source ST systems seems to be the best choice since they represent only 1.4% increase on energy demand, albeit there is the need to find a solution to decrease the peak load, like introducing some kind of demand response strategy that would coordinate the ST backup to work at different off-peak hours.

In the next section, we study an integrated approach that intends to model the real project implementing a mix of ST systems and HP.

Table III.7 - Comparison between actual and possible scenarios

Scenario	**Annual energy load** [MWh/year]	**Peak load** [kW]	**Costs per unit** [€/MWh]	**Total cost of operation** [€/year]
Actual load without electric DHW systems	1377.8	225.5	255	351 404
100% Solar thermal systems	1396.4	478.2	223	311 402
100% Heat pump systems	1502.4	331.0		335 045

4.3 Integrated models

4.3.1 Validation

To validate the model, we compared the integrated model that considers electricity load from the 27 ST and 11 HP that were installed in the first phase and Corvo's electric load for the first half of 2013, which includes already the DHW backup load from the systems that have been installed. We took as an assumption that the island has 1/3 of each demand profile (Table III.4), and used the off-peak model, as this represents the real operation conditions (see Section 3.1.2.). This means that the total estimated load due to the hot water backup service is given by:

$DHWmodel = load\ 27\ STsystems + load\ 11\ HPsystems + load\ 1^{st} semester 2012$

In terms of total energy, we already knew from Figure III.2 that from 2012 to 2013 there was an increase of 5% in residential demand; our model, for the same period, predicts an increase of 4% compared to 2012. The additional 1% may correspond to the average increase of 1% in the residential sector for all the islands in the Azores that occurred between 2012 and 2013.

Looking into detail to the typical load diagrams for winter and summer weeks - represented in Figure III.10 and Figure III.11- there is an evidence of the increase on the overall load of 2012 to 2013 that can be explained with the installation of the DHW systems. In particular, we see that in winter (Figure III.10) the load from 2013 has an extra peak (compared to 2012) that represents the backup of ST devices turning on. The peak in our model is delayed one hour (at midnight), because the clock switches installed in summer/autumn of 2012 were not synchronized for winter time (due to daylight savings). In the summer week, the peaks are already coincident.

The model is not so accurate for the weekend days (the days represented between 1 and 48 hours). The difference, especially on Sundays, may be explained by the assumption in our model that, the DHW demand profile is the same for weekdays and weekends, when in practice we verify that it is not true. For example, in weekends, the morning peak load occurs usually later demonstrating that on weekends the people wake up later (so use DHW later).

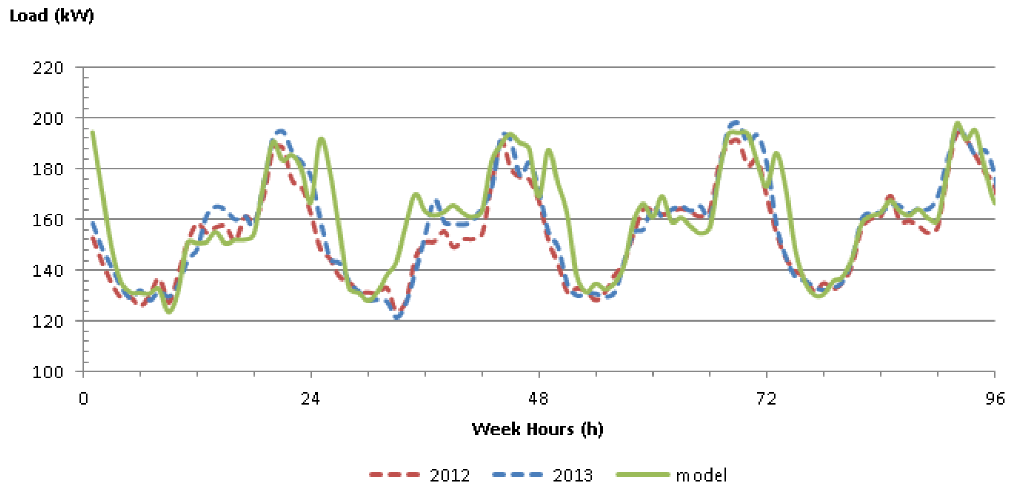

Figure III.10 - Comparison of DHW Model and Validation load for winter

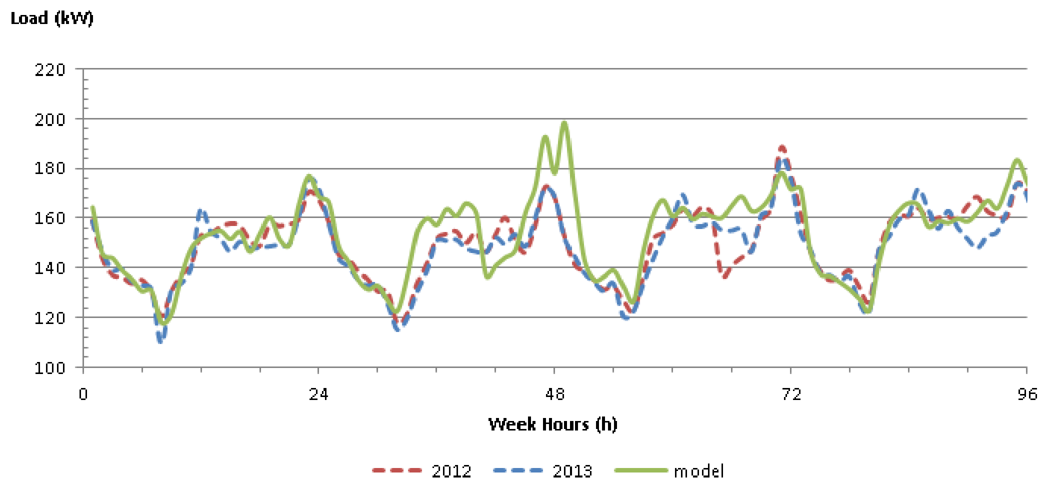

Figure III.11 - Comparison of Model and Validation load for summer

Overall, our model overestimates the load in 0.7%, compared to the average week in winter. In the summer months, the model presents an error of 2%. This behavior can be justified by three factors:

- Real DHW consumption is lower in summer, leading to lower electricity used by HP to satisfy it (the 40 l/ person/day can be overestimated for summer);
- the model assumption of 1/3 for each demand profile is most probably inaccurate; in practice the “evening” consumption profile maybe dominant, leading to less electric backup (more use of the solar energy stored during the day);
- the radiation data used in the model is from the meteorological reference year; the real radiation in the first half of 2013 may have been higher than the one considered in the reference year.

In conclusion, the model overestimates the impact of the DHW backup between 1% in winter and 2% in summer, when compared to the load diagram for the first half of 2013. In the following sections, we estimate the impact of the full implementation of the project, which is expected to be finished in mid-2014, considering different model assumptions.

4.3.2 Simple model

The simple model consists in a proportional load mix of ST and HP (as described in Table III.2) where the backup may be switch on whenever needed. The total electric load from ST and HP is given by:

$$DHWmodel = 144\ systems.(46\%\ STModel + 54\%\ HP\ Model) + previous\ load$$

When we compare Corvo's load to the simple model estimation in Figure III.12, we can observe that when all the systems are installed, the peak load will increase significantly: between 30 and 70% in the morning peak, and 50 to 78% in the evening.

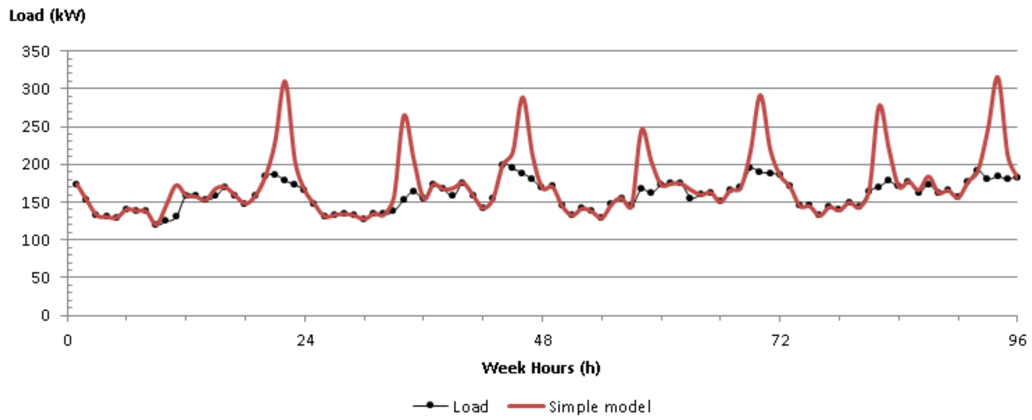

Figure III.12 - Comparison of previous Corvo electric load and simple DHW Model, for Week 10 (winter)

In the morning, if the demand is higher and there is not enough hot water stored in the tanks, all the systems will require electric backup at the same time. In the evening, even if the tank has stored thermal energy but the demand is very large, it will require additional electric backup at the same time of all other appliances (dishwashers, clothes washers, ovens and stoves). This leads to an increase of the peak load around 100 kW, which represents an increase of almost 50%. Although the island generating capacity is 536 kW and therefore is able to handle that increase, this would pose a significant operational stress to the grid, especially to cope with the reliability standard of "*N-1*" spinning reserve followed by EDA in Corvo (which means there must be at least one generator available to replace the generators in operation).

4.3.3 Model with losses

In Figure III.13 and Figure III.14, we test how tank losses influence the simple model.

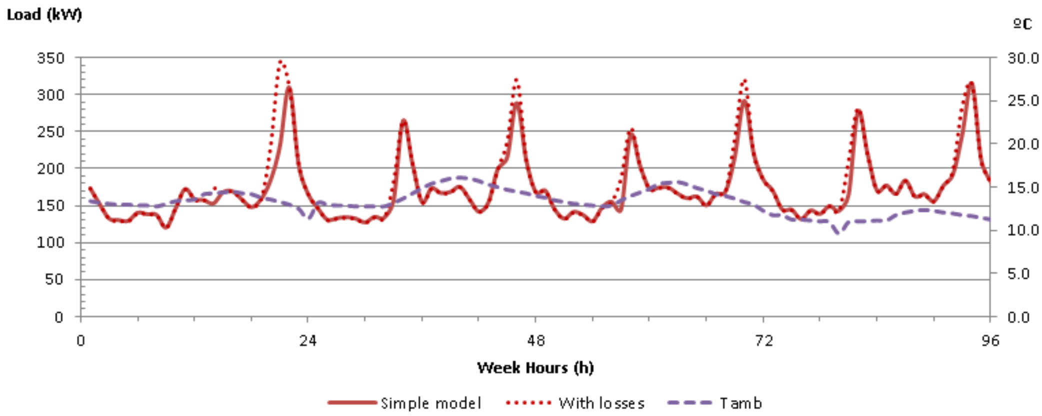

Figure III.13 - Comparison of DHW Model with and without losses, knowing exterior temperature for Week 10 (winter)

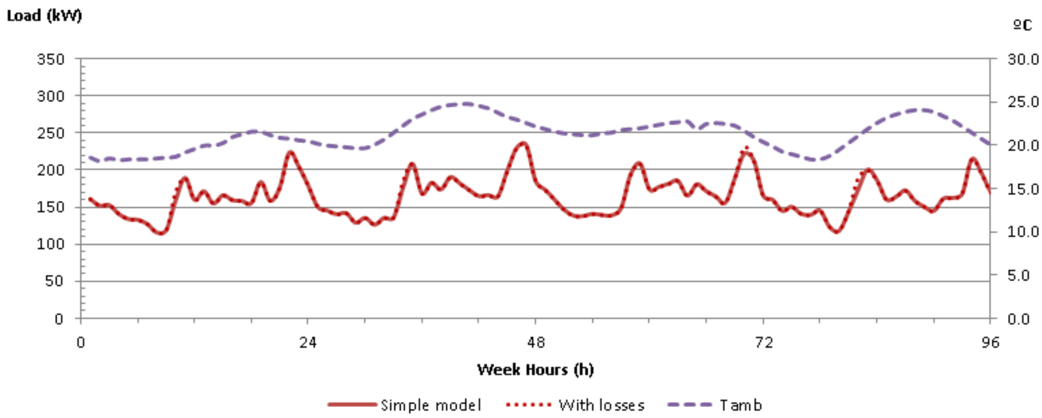

Figure III.14 - Comparison of DHW Model with and without losses for Week 25 (summer)

As we could expect, losses on the storage tanks are more considerable during the winter period, when the difference between storage temperature and exterior temperature is bigger. This leads to higher peaks loads, especially in the morning, since during the night the losses in the tank are higher due to lower exterior temperatures. In spring and summer periods, the simple model and the model with losses do not present considerable differences, which can be explained by higher exterior temperature and solar irradiation, leading to smaller losses. Still, we see that the electric backup peak does not disappear completely in the summer, since heat pumps maintain their cycle of electric load and they are not influenced by the existence of solar energy).

4.3.4 Model with off-peak backup

The idea of forcing electric backup to be done at off-peak periods (here considered between 00h and 08h) is to lower the evening peak load, since the DHW demand (and consequent backup) is normally done at the same time of other electric appliances. This has been the option followed in the island, encouraged by the existence of a dual tariff based and the easiness of implementation using simple clock switches in the power circuit of the electric backup.

In Figure III.15 (winter), we see a decrease of the evening peak and the generation of a new one, every day, at midnight. This is justified by the fact that every DHW system, below the thermal energy needed, will turn on at same time.

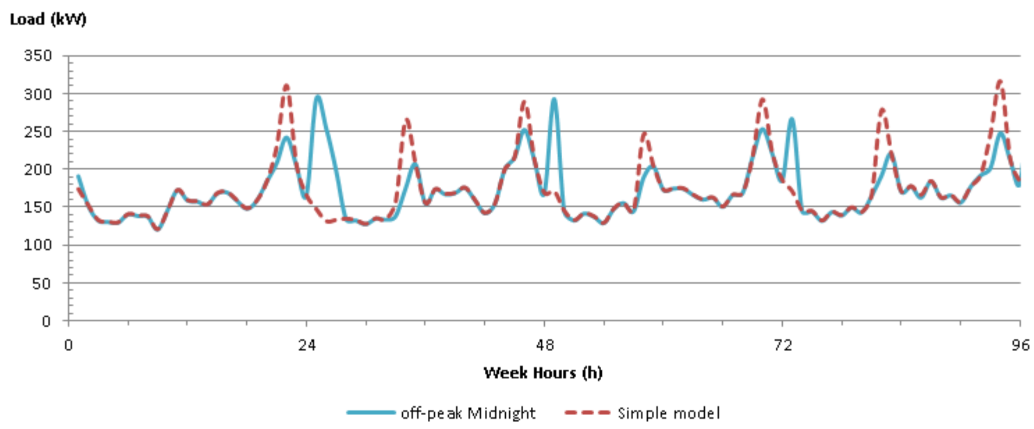

Figure III.15 - Comparison of simple model with free backup and off-peak backup model for Week 10 (winter)

In Figure III.16 (summer), the midnight peak almost disappears, which can be explained by the existence of enough thermal energy stored during the day, due to higher irradiation.

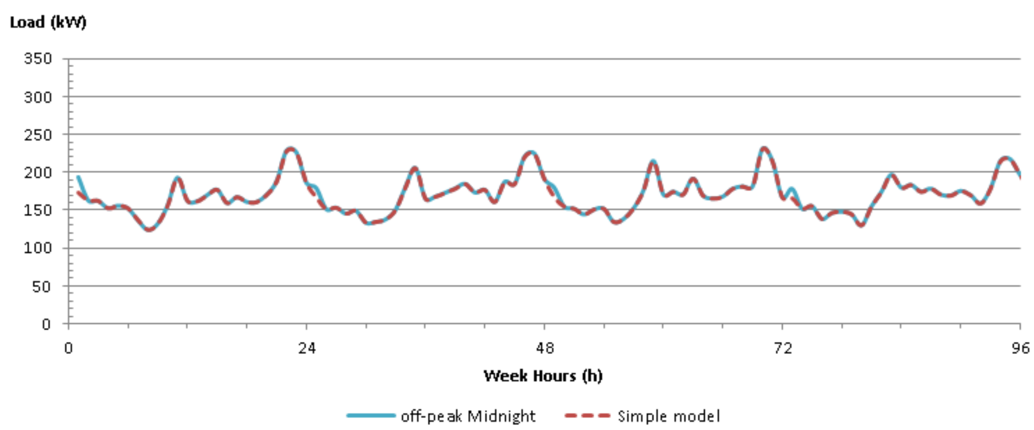

Figure III.16 - Comparison of simple model with free backup and off-peak backup model for Week 26 (summer)

The impact of moving the ST electric backup to off-peak periods, in the morning and evening peaks, is not very significant, as most of the DHW systems are heat pumps that work continuously and its consumption cannot be limited. In fact, although HP systems are 54% of the new DHW systems in Corvo, they have an overall electric consumption impact of 64%.

To avoid the midnight peak introduced in the previous model, we tested a scenario where the backup during off-peak period is distributed along the night. Depending on consumer's profile, the backup switches at different hours: to morning profile users will turn on at 6 h, to evening users at 4 h, and to the distributed users at 2 h. In Figure III.17, we can see the significant impact in the peak load that this option introduces: the midnight peak of the previous model (around 300 kW) is divided into three smaller peaks. This corresponds to the turning on/off of the systems with different consumption profiles. However, the evening peak (around 250 kW) is not solved with this approach, which suggests that HP are responsible for that increase, since technologically it is impossible to limit the use of backup in this case.

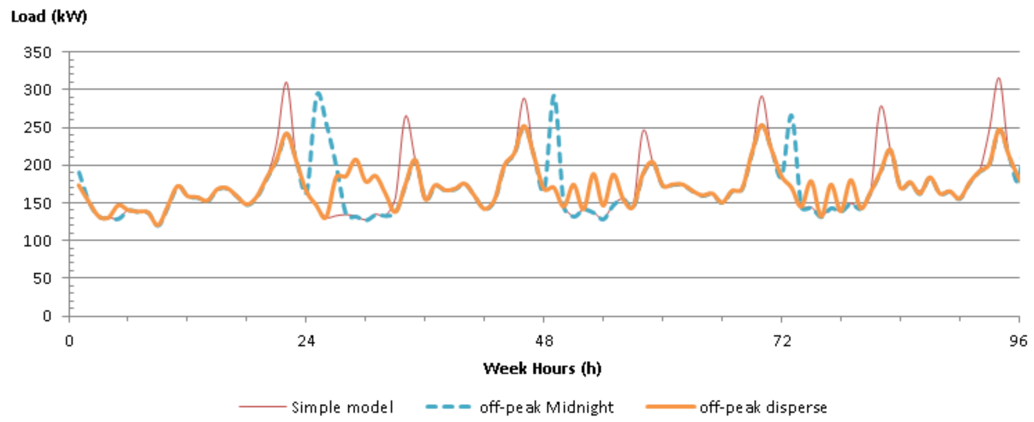

Figure III.17 - Comparison of off-peak backup model with disperse off-peak model for Week 10 (winter)

4.3.5 Model with off-peak backup with losses

In this model, we tested together the losses previously calculated in Section 3.3.3 and the backup hour limitations imposed in 3.3.4 to study if night losses have a significant impact on the load.

In Figure III.18, we found that the losses in the storage tank increases slightly the midnight peak load. Since losses are proportional to ambient temperature, we verify that they are higher during the night period, increasing in winter, the midnight peak even more than the evening peak.

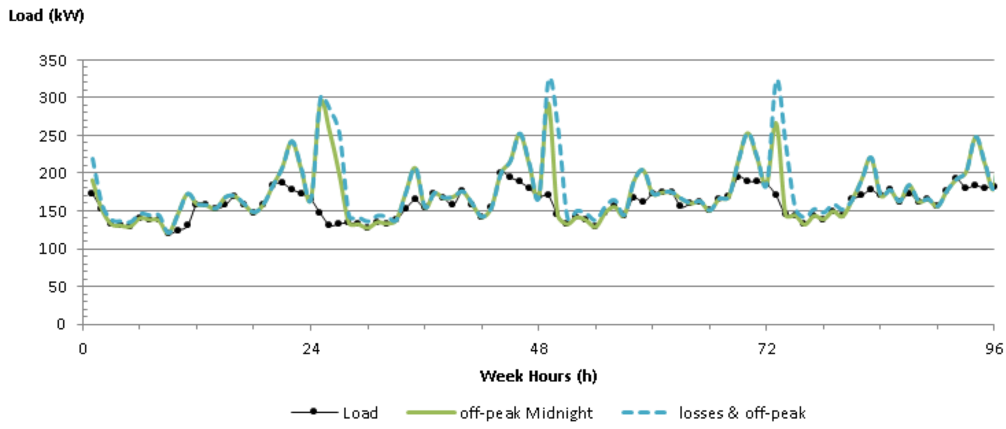

Figure III.18 - Comparison of off-peak backup model with and without losses for Week 10 (winter)

4.4 Energy and peak load for different models

Table III.8 summarizes the essential differences in terms of peak loads and energy demand for the different models.

The overall energy demand is quite similar between models, representing, in the worst case (losses & off-peak), an increase of 10.3 % in the annual electric load. The simple model is the one that presents the lower increase with 6.7% and that is due to the maximization of solar energy in the systems.

However, the greatest impact is in the peak load is given by the simple and losses model, which has risen in 60% and 61% of the initial peak load, respectively. This is a huge increase and constitutes a great challenge to grid management. That is why we considered moving DHW backup to off-peak hours, which represents, in the midnight model, an increase of only 49% in the peak load. The model with the distributed off-peak load is the one with the lower impact, with only 24% increase. It is interesting to observe that the fact of having backup when is needed will increase the peak load but will be more effective in terms of energy consumption: the simple model presents higher peak load but lower energy demand.

In terms of costs, any of the electrified DHW models introduce savings when compared to the base model, although the cost related to the increase on the peak load is not specified on it. The best solution would pass through a minimization of operation costs and peak load, that, in this study, would be the off-peak distributed (21 200€ annual savings).

Table III.8 - Final energy, peak load and cost comparison between different models

	Peak load [kW]	**Δ Peak load** [kW]	**Peak increase** [%]	**Energy demand** [MWh/year]	**Δ Energy Demand** [MWh/year]	**Energy increase** [%]	**Ave. daily energy demand** [kWh/day]	**Annual savings** [k€]
Initial load	225.5	0	0.0%	1377.8	0	0.0%	3827.2	0
Simple model	360.3	134.8	59.8%	1470.3	92.5	6.7%	4028.2	23.5
With losses	363.7	138.2	61.3%	1484.8	107.0	7.8%	4068.0	20.3
Off-peak midnight	336.3	110.8	49.1%	1482.7	104.9	7.6%	4062.2	20.8
Off-peak distributed	279.4	53.9	23.9%	1480.5	102.7	7.5%	4056.3	21.2
Losses & off-peak	354.9	129.4	57.4%	1519.8	142.0	10.3%	4163.9	12.5

5 Conclusions

In this study, we proposed a new hourly model to estimate the impact of domestic hot water systems (solar thermal and heat pump) on the electric generation of an isolated microgrid. We validated the model using real load data from the island of Corvo, which is currently implementing this type of systems in every household. We also demonstrated that the impact may be significant for small grids, by analyzing different scenarios of backup scheduling and consumption profiles of the hot water service.

In detail, we concluded that although heat pumps have less impact on peak load than solar thermal systems, they represent higher overall electricity needs. In summer, ST backup is in general negligible, while in winter, even changing the solar thermal backup to the off-peak period, they can be responsible to increase almost 50% of the peak load. We also demonstrated that the best scenario is to limit and distribute the backup along off-peak hours, achieving 25% increase in the peak load and 7.5% on the annual energy demand, albeit not being the scenario with the biggest annual saving. The simple model (with 23 500€ savings) would not be reasonable since it represents an increase of almost 60% on peak load, and that would lead to more investment on the electric capacity of the island.

The proposed model presents a significant contribution to understand the dynamics of integrating renewable resources at different scales, spanning from the household level to microgrids. The time resolution can also be adjusted and, therefore, used to study the application of demand response strategies at the household or neighborhood level, as well as to optimize dispatching models of small networks like the Corvo Island.

As future work, we will use this model to design scheduling techniques for the DHW backup that optimizes the operation of the power plant in Corvo, by adjusting the electric load to improve the dispatching strategy of the diesel generators, with and without the contribution of a wind power plant or a small pump-hydro facility.

Acknowledgements

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Chapter IV
Optimal electricity dispatch on isolated mini-grids using a demand response strategy for thermal storage backup with genetic algorithms

Abstract

The present study uses the domestic hot water (DHW) electric backup from solar thermal systems to optimize the total electricity dispatch of an isolated mini-grid. The proposed approach estimates the hourly DHW load, and proposes and simulates different demand response (DR) strategies, from the supply side, to minimize the dispatch costs of an energy system.

The case study consists on optimizing the electricity load, in a representative day with low solar radiation, in Corvo Island, Azores. The DHW backup is induced by three different demand patterns. The study compares different DR strategies: backup at demand (no strategy), pre-scheduled backup using two different imposed schedules, a strategy based on linear programming, and finally two strategies using genetic algorithms, with different formulations for DHW backup – one that assigns number of systems and another that assigns energy demand. It is concluded that pre-determined DR strategies may increase the generation costs, but DR strategies based on optimization algorithms are able to decrease generation costs. In particular, linear programming is the strategy that presents the lowest increase on dispatch costs, but the strategy based on genetic algorithms is the one that best minimizes both daily operation costs and total energy demand, of the system.

Keywords

Demand response; Thermal storage; Domestic hot water; Renewable energy; Genetic algorithms; Linear programming

1 Introduction

The increase in the use of micro-generation technologies has been introducing new challenges and opportunities to the electricity grid management. With the development of smart grids, the consumers can also participate in the control of the load, but this requires new approaches to optimize the grid operation, such as demand response [1].

According to [2], demand response is voluntary and temporary adjustment of power demand taken by the end-user as a response to a price signal, for example market prices or tariffs, or taken by a counter-party like the utility based on an agreement with the end-user. The use of demand response strategies is a way to increase the flexibility of the grid management, as it allows the rescheduling of part of the load, adjusting the demand to the supply, deferring the need to invest more in capacity [3].

In small and isolated systems, like islands or remote communities, where the residential sector often represents the largest share of energy demand [4], the access to goods, including energy resources, is in general limited. In these cases the reliability of the grid operation is a critical aspect, especially when integrating renewable energy supply. The use of demand response strategies may help to deal with the intermittency of renewable resources, by contributing to the balance of demand and supply, thus minimizing operation costs and inducing a more reliable grid management [5]. As claimed by many authors [6][7], renewable integration can be further optimized, if storage systems are coupled with demand response in order to enlarge the load shifting capacity.

In [8], the reschedule of water heaters is identified as one of the demand response strategies with largest potential on the residential sector. In order to study the potential of the electric backup of residential thermal storage as demand response strategy in isolated systems, the authors discussed in [9] the impact in the overall electricity load, in the small island of Corvo, Azores. Similarly to electric vehicles and their capacity to absorb energy from the grid, acting as a demand response agents, hot water tanks can also be used for peak power shaving or load shifting, acting as a storage system and helping (if it is the case) to smooth renewable integration [10][11].

In [7], there is an extensive review of demand response strategies and techniques, but most of them consider the end-user point of view, based on the use of feed-in tariffs in order to change their normal demand pattern. From the utility point of view, to optimize the load management, [12] uses a multi-objective integer linear programing approach while [13] uses genetic algorithms.

This paper proposes and analyses of the impact of different demand response strategies from the grid operation point of view. The objective is to minimize the island's energy generation and dispatch costs, avoiding high power peaks and achieve lower operational costs. In particular, it introduces new approaches based on linear programming and genetic algorithms to implement a demand response strategy of residential thermal storage.

The paper is organized as follows. Section 2 describes the problem statement and presents the characteristics of the case study. Section 3 introduces the models used for optimal electric dispatch and for quantifying the domestic hot water backup impact on the grid. Section 4 presents the different optimization strategies to implement the demand response strategies. The results are presented and discussed in Section 5, and Section 6 draws the conclusions of the work.

2 Problem statement of the case study of Corvo Island

The challenges of grid management and electric dispatch in small and isolated grids with renewable micro-generation systems, have been the scope of many recent studies and implementation projects [4]. This paper proposes to minimize the economic dispatch of an isolated system using a demand response approach to manage the domestic hot water electricity backup loads. The use of a DR program may have the additional benefit of delaying the investment of increasing the installed thermal generation capacity, to deal with the higher peaks. For that purpose, different optimization strategies of hot water backup are tested, in order to minimize the costs of the Corvo Island electricity generation and dispatch, from the grid manager point of view.

The analysis of the demand response strategy is done using the case study of Corvo Island, an isolated island in the middle of the Atlantic Ocean, with 430 inhabitants living in 144 houses [14]. At the moment Corvo Island, is externally dependent on energy resources, particularly diesel to supply the electricity generation power plant, with an installed capacity of 536 kW [15]. On the other hand, the recent replacement of gas boilers systems to generate domestic hot water, through the installation of 66 solar thermal systems and 78 heat pumps, has been a step forward to achieve energy autonomy, by assuring the continuous supply of DHW that, in the past, suffered from shortcoming of liquefied petroleum gas (LPG) to the island [9].

The annual load of the island, prior to the electrification of DHW, was around 1.4 GWh with a daily peak of 225 kW and a daily consumption of 3.8 MWh. The load diagram is similar in weekdays and weekends, which is explained by the absence of industry in the island and the existence of few service buildings. The 2012 average daily load diagram is shown on Figure IV.1, with the annual hourly variability and daily seasonal variability. The peak power is observed at dinner time, and the variability is similar from summer to winter, being the average load higher in the summer but the maximum peak in winter.

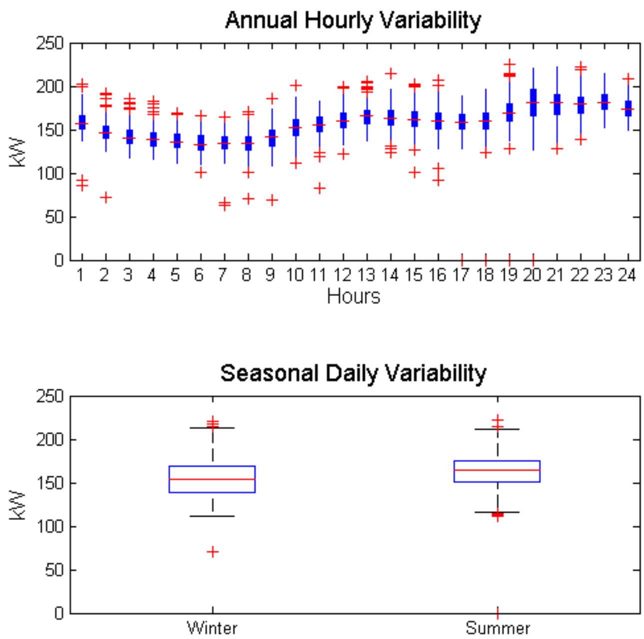

Figure IV.1 - Daily load diagram for Corvo Island: 2012 hourly variability; winter and summer daily variability

The electricity power plant of Corvo is composed of four diesel generators with the characteristics described in Table IV.1.

Table IV.1 - Diesel Generators characteristics and constraints

Generator		*#1*	*#2*	*#3*	*#4*
Total Base power [kVA]		135		200	
Nominal Power - Pnom[kW]		108		160	
Minimum power output [kW]		42		64	
Fuel Consumption [l/h]	100% Pnom	31.2		49.4	
	75% Pnom	24.2		37.4	
	50% Pnom	17.4		25.6	
Minimum up time [h]		4		5	
Minimum down time [h]		2		3	
Ramp up/down rate [kW/h]		Inf		Inf	
Start-up cost (cold/hot) [€]		20/0		30/0	
Shut down cost [€]		0		0	
Working hours in 2012 [%/year]		49%	63%	49%	44%

The DHW electric backup increased the overall island electricity demand [9]. However, it is important to guarantee that the peak demand remains within the power plant limits, otherwise an investment on additional generation capacity is required. In the case of Corvo Island, the generators should operate at least at 50% of their maximum load and the power plant has in general N-1 generators in operation due to reserve requirements, requiring the use of demand response strategies. Therefore, if DHW backup could be evenly distributed over the off-peak period using a demand response program, it could contribute to guarantee the operation at the optimal operation point.

3 Modeling the optimal dispatch

In this section we present separately the two models that will work together to achieve optimal economic dispatch using DHW backup needs as demand response agent. First we derive the economic dispatch model, using the operational and technical constraints which are used also in Corvo Island, and then we introduce the DHW electric impact model, also validated in Corvo Island in [9].

3.1 Economic dispatch model

In this work, we consider the use of an economic dispatch model that combines the unit commitment problem and the quadratic dispatch method, taking into account the operational restrictions of generation technologies [16]. The model was built in *MATLAB* [17] and works with an hourly time-step, calculating for each hour the generation and dispatch costs.

The economic dispatch model is represented by Equation IV.1:

$$Minimize\ [\,F_{total}(P_{total})] = \sum_{i=1}^{N} F_i(P_i) \tag{IV.1}$$

where the objective function F_{total} is the total cost for supplying a certain load (P_{total}), which is the sum of generation cost $F_i(P_i)$ of each individual thermal unit *i* generating a power P_i (in a total of N). The total load (P_{total}) is the sum of the power supplied by the various generators (P_{load}), plus the losses on the distribution network (P_{loss}), represented in Equation IV.2:

$$P_{load} + P_{loss} - \sum_{i=1}^{N} P_i = 0 \tag{IV.2}$$

The optimization approach is a forward dynamic programming algorithm, that evaluates the best transition, from the current state at a given hour to the state at the next hour [18]. It is assumed that a state consists of an array of units, with a certain number of operating units while the rest of the units are off-line. All the combinations of commitment of the 4 generators (2^4-1) are considered in Table IV.2

Table IV.2 - Possible combination of committed generators

Total Committed Power Capacity [kW]	**Possible combination of committed generators**
536	(#1+#2+#3+#4)
428	(#1+#3+#4) or (#2+#3+#4)
376	(#1+#2+#3) or (#1+#2+#4)
320	(#3+#4)
268	(#1+#3) or (#1+#4) or (#2+#3) or (#2+#4)
216	(#1+#2)
160	(#3) or (#4)
108	(#1) or (#2)

The state of an array is considered to be feasible, for a particular hour, if it obeys Equation IV.3

$$\begin{cases} min\,(C_j) \leq D - SRd \\ \qquad\qquad \wedge \\ \max(C_j)\ \geq D + SRu \end{cases} \tag{IV.3}$$

where C_j is the power capacity of the state *j, D* the demand and *SRd* and *SRu* the spinning reserve downwards and upwards, respectively.

To determine if a state is feasible or not (even if each previous state is feasible itself), the model considers the need to have an operating spinning reserve and additional operational constraints:

- minimum up/down time: is the minimum amount of time a unit should remain running/resting once it is synchronized/turned off;
- ramp up/down rate: is the maximum possible ramp up/down rate for a generator power production to rise/decrease between two time steps;

- start-up/shut-down costs: in thermal units start-up/shut-down costs have to be considered since there is a certain amount of energy that has to be expended to bring the unit online/off-line, avoiding to start/shut down these units arbitrarily.

The algorithm that searches for the feasible states of generation considering all these constraints is presented in Figure IV.2.

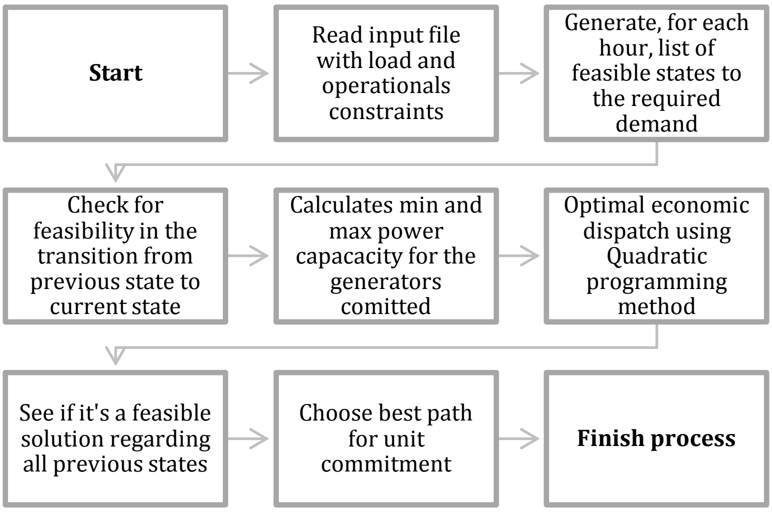

Figure IV.2 - Electric dispatch model

3.2 Domestic hot water model

The electrification of domestic hot water introduces additional loads to the grid. To estimate that impact, it was used a model introduced in a previous work [9]. This model has an hourly resolution and was developed and validated for the case study of Corvo Island, considering the installation of 66 solar thermal collectors (ST) and 78 heat pumps (HP) for domestic hot water. Figure IV.3 presents the solar potential of Corvo Island, on a 30º plane, south oriented, where an average of 4000 W/m^2/day of daily solar irradiation is observed. When the energy in the hot water tanks is low and the daily solar irradiation is less than 2000 Wh/m^2/day, the solar systems will not be able to respond to 100% to DHW demand [9].

The model presented in [9] and here summarized, is based on an hourly energy balance between the DHW demand, the storage tank size and electric backup. For each individual solar thermal system the energy balance is done according to the set of Equations IV.4, IV.5 and IV.6:

$$\mathrm{Q}_{DHW}(t) = C_{p\,water}.\rho_{water}.V_{DHW}(t).(\mathrm{T}_{\max} - \mathrm{T}_{\text{inlet}})\ [kW] \qquad \text{(IV.4)}$$

$$Q_{Tank}(t) = Q_{Tank}(t\text{-}1) + Q_{solar}(t) + Q_{backup}(t) - \mathrm{Q}_{DHW}(t);\ \ 0 \leq Q_{Tank}(t) \leq Q_{Tank}max\ [kW] \qquad \text{(IV.5)}$$

$$Q_{backup}(t) = \mathrm{Q}_{DHW}(t) - Q_{solar}(t) - Q_{Tank}(t\text{-}1);\ \ 0 \leq Q_{backup}(t) \leq P_{nom}\ [kW] \qquad \text{(IV.6)}$$

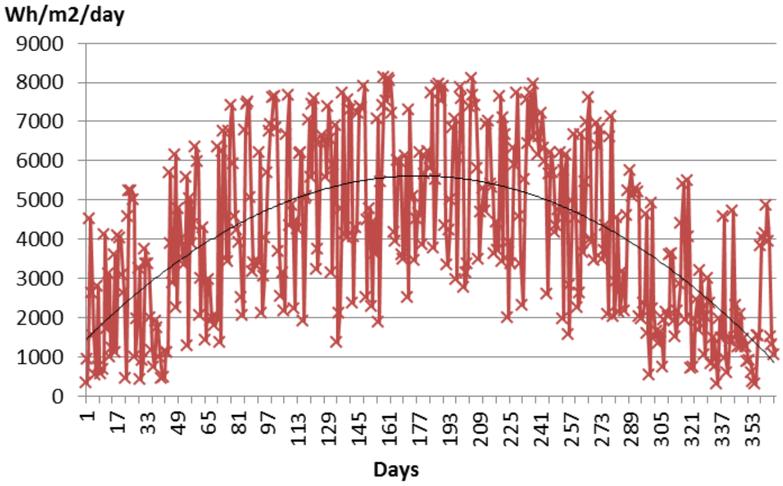

Figure IV.3 - Daily Irradiation on 30º surface in Corvo Island

where:

- $Q_{DHW}(t)$ is the hourly DHW thermal needs, $C_{p\,water}$ the specific water heat, ρ_{water} the water density, V_{DHW} the volume of hot water demand and T_{max} and T_{inlet} the maximum and inlet water temperature, respectively, in the system;
- $Q_{Tank}(t)$ is the hourly energy stored in the tank and $Q_{Tank}max$ is the maximum storage capacity;
- Q_{solar}(t) is the hourly solar gains through the solar collectors;
- $Q_{backup}(t)$ is the hourly electric backup needs of the ST system;
- P_{nom} is the nominal power of the electric resistance in the storage tanks.

For heat pumps the energy balance is given by previous Equation IV.4 and the new set of Equations IV.7, IV.8 and IV.9:

$$Q_{Tank}(t) = Q_{Tank}(t\text{-}1) + Q_{HP}(t) - Q_{DHW}(t)\ ;\ 0 \leq Q_{Tank}(t) \leq Q_{Tank}\ max\ [kW] \tag{IV.7}$$

$$Q_{HP}(t) = \left(Q_{Tank}\ max - Q_{tank}(t\text{-}1)\right);\ 0 \leq Q_{HP}(t) \leq\ P_{nom}[kW] \tag{IV.8}$$

$$W_{HP}(t) = \frac{Q_{HP}(t)}{COP}\ [kW] \tag{IV.9}$$

where:

- $Q_{HP}(t)$ is the hourly thermal energy needed by the heat pump;
- $W_{HP}(t)$ is the hourly electricity needs of the HP;
- COP is the Coefficient of Performance of the heat pump.

A more detail description of how the model works is presented in Figure IV.4. First, we defined the DHW demand profiles (daily and hourly) in liters of water per system and categorized them in groups of consumers (morning and evening uses, and distributed uses along the day), which are presented in Figure IV.5. Then, the ST and HP system characteristics (described in Table IV.3) were defined in order to meet the daily hot water demand. In the second phase, the solar potential, the thermal energy stored in the tanks and the thermal energy consumed at each hour were calculated, and from that the electric backup needs for each system were obtained. On the last step, the needs of electric backup of each group of consumers were integrated to estimate the total impact on the island mini-grid and finally different backup scheduling strategies were tested.

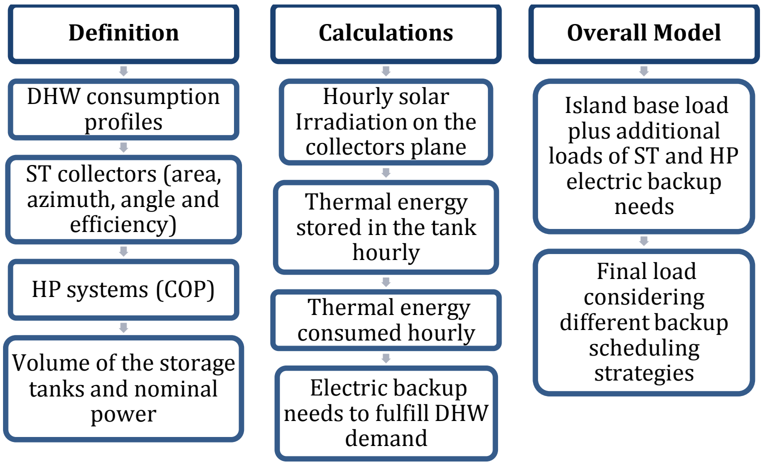

Figure IV.4 - DHW model regarding its impact on the grid [9]

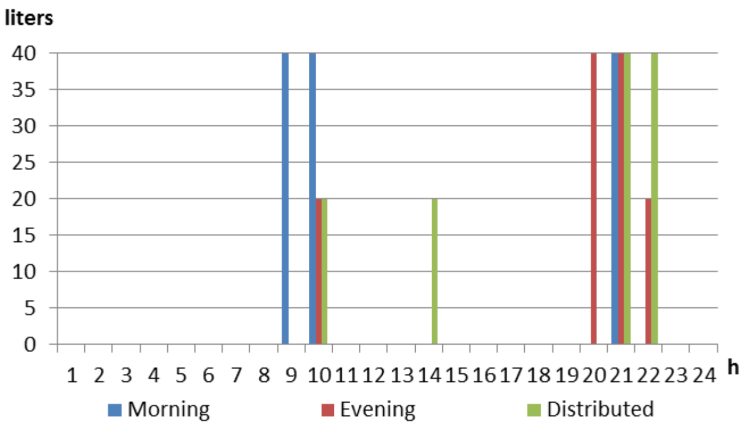

Figure IV.5 - Assumed profiles of DHW demand in Corvo Island [9]

Table IV.3 - DHW systems relevant parameters [9]

Solar Collector				**Heat Pump**		**Storage Tank**	
Area [m²]	η [%]	ε [%]	Fluid	COP	Type	Volume [l]	Power [kW]
4.2	80	80	Water	2.5	Air-Water	200	2.3

4 Demand response strategies

The aim of using a demand response strategy to aid in the optimal dispatch is to manage the power generated hourly along the day, minimizing the generation and dispatch costs. To test different demand response strategies for the DHW backup, a typical day with low solar irradiation, was chosen. Table IV.4 summarizes the different demand response strategies that have been developed and tested, which are described in detail in the following Sections 4.1, 4.2 and 4.3.

Table IV.4 - Description of the different methods to test demand response of DHW loads

Dispatch strategies	Genetic Algorithms
i. Only base load (without DHW load) ii. DHW at demand (no dispatch constraints) iii. DHW off-peak midnight iv. DHW off-peak disperse v. Linear programming when load <=170 kW	The optimal dispatch model is used as fitness function and the population represents the schedule of hourly loads in terms of: • number of systems with different load profiles: *GA_sys* • daily amount of energy needed, taking in account solar fraction for a representative day: *GA_E*

At the end, all the scenarios were compared between each other and with the *Strategy i – base load* (island load prior to the installations of DHW electric appliances) and *Strategy ii - DHW at demand* (model described in Section 3.2, where electric backup is done without constraints).

4.1 Demand response based on heuristics

The simplest demand response strategies consist of implementing one of two simple heuristics:

- *Strategy iii - DHW off-peak midnight*: the backup is limited to off-peak hours (1h-8h) starting at midnight; this represents the installation procedure often used in the residential sector ;

- *Strategy iv - DHW off-peak disperse*: the backup limited to off-peak hours but distributed on different periods according to different groups of consumers (2h-3h/ 4h-5h/ 6h-8h).

4.2 Demand response with linear programming

In Table IV.1, we can observe that the optimal performance of both types of generators is achieved at 65% of their nominal power. In order to assure a constant dispatch of 65% of their capacity, the minimum total load should be 170 kW at all times (65 %×(108 kW+160 kW)≅170 kW). In this way, a linear programming demand response strategy that optimizes the DHW production to guarantee a minimum of 170 kWh load was tested - *Strategy v - Linear programming when load <=170 kW*.

This model uses a linear programming optimization (*linprog MATLAB* function), to optimize the hours at which the DHW load is placed. The cost function is presented in Figure IV.6 and the minimization problem and its constraints are described by Equation IV.10 and IV.11:

$$\min\,[f(x)] = \sum_{j=1}^{3}\sum_{i=1}^{24} a_{ji}x_{ji} \tag{IV.10}$$

$$\begin{cases} \sum_{i=1}^{24} x_{1i} = \sum_{i=1}^{24} x_{2i} = \sum_{i=1}^{24} x_{3i} = \textit{Daily DHW backup group load} \\ \sum_{j=1}^{3}\sum_{i=1}^{24} x_{ji} \leq 170\ kW - demand\ (i) \end{cases} \tag{IV.11}$$

Where:

- j is the water profile (*1 – morning, 2- evening, 3 – distributed*);
- i is the hour of the day;
- x_{ji} is the energy of backup for a certain group of users, for a certain hour;
- a_{ji} is the cost of having backup load for a certain group of users for a certain hour.

This cost function varies with the consumption profile (see Figure IV.6) and obeys the following conditions:

1) The electricity cost of generating DHW after the time of consumption is maximum and equal to 1€;
2) it has an hourly decrease rate of 0.1 €/h;
3) it assumes the minimum value of 0.1 € at the hour of consumption of the hot water and the previous hour.

These conditions were imposed in order to minimize thermal losses on the hot water tank, so the cost function will be different for the three different demand patterns defined earlier ("Morning", "Evening" and "Distributed").

Taking as example the morning profile, the cost of electricity to heat the water in the tank is decreasing from its maximum (1 €) at 22h, until it achieves its minimum (0.1 €) at the hour before the demand (8h) and demand hour (9h, 10h). Then, it raises again to the maximum at the hour just after demand, and decreases again until the hour before the next demand (20h).

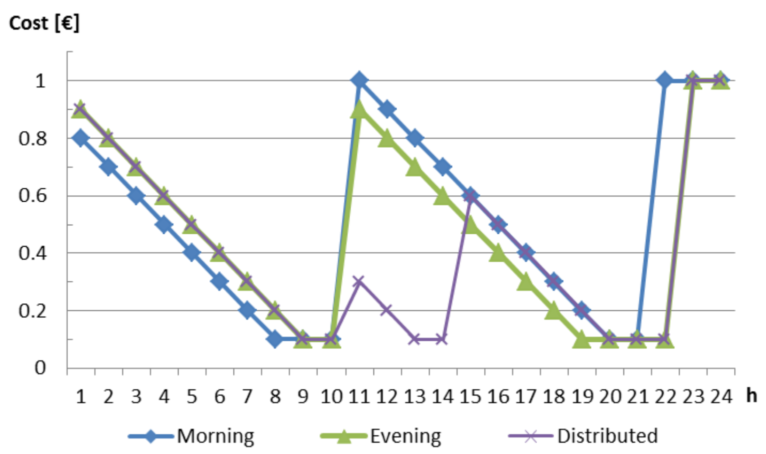

Figure IV.6 - Profile cost for linear programming optimization for placing DHW loads

4.3 Demand response with genetic algorithms

Genetic algorithms (GA) is a meta-heuristic approach of optimization, first used by J. H. Holland in 1975 [19]. This stochastic optimization algorithm is based on natural evolution principles and genetic concepts like natural selection, crossover and mutation and has been applied to a large range of problems, from engineering, mathematics, biology, etc., especially on constrained optimization problems [20][21]. In these algorithms, a population of *n* chromosomes (possible solutions) is generated and then exposed to a fitness function. Each individual is evaluated in terms of response to fitness. The fittest chromosomes (parents) are most likely to be selected to the next generation and then they are crossed over and mutated, giving origin to another population of possibly better fitted chromosomes (children). This cycle is repeated through *m* generations, and terminates when a maximum number of generations is achieved or when a stopping criterion is met as, for example, when the fitness of the population does not evolve after few generations. These algorithms are versatile, since they are easy to implement and adapt to constrained problems.

4.3.1 Applying GA to the economic dispatch problem

To optimize the placement of DHW backup of ST systems along the day (since the heat pumps present little flexibility to change the hour of backup [22] and, as such, were not considered as shiftable), the genetic algorithms are introduced to minimize the fitness function, that corresponds to the dispatch model of Section 3.1. Two different ways to formulate the problem were developed:

a) each chromosome represents an amount of systems that operate at each hour;
b) each chromosome represents an amount of energy demanded at each hour.

In both cases, the three profiles of demand described earlier in Figure IV.5, were considered.

Table IV.5 describes the problem's constraints that were applied to each formulation. In particular, it addresses the maximum energy demand required per day and the maximum number of systems or admissible load, per hour.

Table IV.5 - Problem constraints

	Systems	**Nominal power per system**	**Maximum Electric Demand per system**	**Maximum Demand per profile**	**Maximum power per hour**	**ST backup**		
						At demand	**Off-peak midnight**	**Off-peak disperse**
Profile	[nº]	[kW]	[kWh/day]	[kWh/day]	Systems / kW	[kWh/day]		
Morning	22	2.3	6.28	138.16	60 sys / 50.6 kW			
Evening	22	2.3	6.28	138.16	60 sys / 50.6 kW	63.1	117.6	117.6
Distributed	22	2.3	6.28	138.16	60 sys / 50.6 kW			
Island total	66	50.6	414.48	414.48	180 sys/ 152 kW			

4.3.2 Population

To model one day of 24 h we used 72 elements (*number of genes*), in order to distribute the load over the 3 hot water profiles through the 24h. The chromosome has the following structure:

$[x_{1\,1}\, x_{2\,1}\, x_{3\,1} \quad x_{1\,2}\, x_{2\,2}\, x_{3\,2} \quad x_{1\,3}\, x_{2\,3}\, x_{3\,3}\ \cdots\ x_{1\,i}\, x_{2\,i}\, x_{3\,i} \cdots\ x_{1\,24}\, x_{2\,24}\, x_{3\,24}]$

where $x_{1\,i}, x_{2\,i}, x_{3\,i}$, $i = [1{,}24]$ h are the DHW electric loads at each hour for *morning (1)*, *evening (2)* and *distributed (3)* profiles, respectively.

The population is made of n chromosomes (*population size*), being the population dimension equal to *[n x 72].*

- After the population is generated, it is filtered through a validation function that imposes some constraints to each chromosome according to Table IV.5:
- The sum of the elements of each chromosome has to be equal to the total daily demand (Equation IV.12), that will differ for each scenario;
- The sum of the elements of same profiles (*1, 2 or 3*) has to be equal to the number of systems/amount of energy (Equation IV.13).

$$\sum_{i=1}^{24}(x_{1\,i} + x_{2\,i} + x_{3\,i}) = Maximum\ daily\ demand \qquad \text{(IV.12)}$$

$$0 \le x_{1\,i}, x_{2\,i}, x_{3\,i} \le Maximum\ power\ per\ hour\ per\ profile = 22\ sys\ or\ 50.6\ [kW] \qquad \text{(IV.13)}$$

4.3.3 Fitness function

The fitness function *f (population)* used was the economic dispatch model described in Section 3.1. As load input, the island base load plus the additional electricity backup proposed by each chromosome was used (hourly DHW load in number of switched on systems on nominal power or amount of energy). The output is the daily dispatch cost plus a penalty (described in 4.3.5) in order to evaluate the total cost of each solution (Equation IV.14).

$$f(population) = economic\ dispatch\ function + penalty \qquad \text{(IV.14)}$$

4.3.4 Penalties

In order to filter solutions (chromosomes) that are far from meeting the problem constraints, penalties were imposed to the chromosomes that did not meet group profiles constraints, as described in Equation IV.15, IV.16 and IV.17:

$$if\ \sum_{i=1}^{24}(x_{1\,i} + x_{2\,i} + x_{3\,i}) = max\ daily\ demand\ \wedge$$

$$\sum_{i=1}^{24} x_{1\,i}, \sum_{i=1}^{24} x_{2\,i}, \sum_{i=1}^{24} x_{3\,i} = max\ profile\ daily\ demand\ \rightarrow penalty = 0 \qquad \text{(IV.15)}$$

$$if\ \sum_{i=1}^{24}(x_{1\,i} + x_{2\,i} + x_{3\,i}) < max\ daily\ demand\ \rightarrow penalty = penalty^2 \qquad \text{(IV.16)}$$

$$if\ \sum_{i=1}^{24}(x_{1\,i} + x_{2\,i} + x_{3\,i}) > max\ daily\ demand\ \rightarrow penalty = \frac{1}{2}penalty^2 \quad \text{(IV.17)}$$

Being the penalty given by Equation IV.18:

$$penalty = \left\| \left(\sum_{i=1}^{24} (x_{1\,i} + x_{2\,i} + x_{3\,i}) \right) - max\ daily\ demand \right\| * penaltyfactor\ \wedge$$

$$penaltyfactor = 10 \quad \text{(IV.18)}$$

The fact that penalties are given with different weights, is related to what we prioritize more in a chromosome [23]. Equation IV.15 evidences that no chromosome is penalized if the total daily demand is equal to the sum of each profile demand, and if it respects the amount of demand of each group of consumers. Otherwise, it applies a penalty (Equation IV.18), based on a penalty factor (of one order of magnitude), in two differential ways:

- if the solution is lower than daily demand (Equation IV.16), the penalty is higher (the square of the penalty), because it causes a problem of satisfaction for the end-user, and that should be avoided;
- if the solution exceeds daily demand, it means that the end-user satisfaction is met, at the expense of some excess energy generation, so the penalty applied is half of the initial penalty (Equation IV.17).

This differential penalty application runs according to the model prioritization for hot water security of supply, rather than the possibility of some excess of electricity, which in practice may not occur, as the tanks have a thermostat that cuts the backup whenever the tank is full of hot water.

4.3.5 Selection function

To select the fittest chromosomes to offspring for the next generation, there are different methods like roulette wheel, tournament, stochastic, etc. [17].

In this work the tournament method was chosen, since is commonly used for minimization problems. This function chooses each parent (chromosome) by randomly choosing tournament size players, then filtering the best individual out of that set, to be a new parent in the next generation. A tournament size of 2 was used.

4.3.6 Cross-over and Mutation

Cross-over is an important operator, since it will cross the information of two (or more) *parents* to origin a new *child* (chromosome) [24]. The method used was the single point cross-over of two parents, with a probability of cross-over of 70% which means it applies to 70% of the population.

Mutation is a very occasional and independent process that makes small changes in the individuals [24]. Due to its probabilistic existence, normally it happens with a random exchanging of genes on a certain element. For the problem here considered, a uniform mutation with a probability of 5% was used.

5 Results and discussion

5.1 Demand response heuristics and linear programming

Table IV.6 presents the results of Corvo Island electric dispatch, using the DHW impact model coupled with economic dispatch of total load, for a representative day with low irradiation. The diesel cost is considered to be 0.54 €/l. Generation costs, which relate only to diesel consumption, and dispatch costs, that account generation costs and start-up and shut-down costs of the generators, are presented.

The first aspect that Table IV.6 highlights is the fact that, for a representative day, the daily thermal demand of DHW can be, in part, assured by solar gains: 414.5 kWh is the maximum daily thermal demand of DHW from ST collectors (in the absence of solar gains) and 185 kWh of the heat pumps, but *Strategy ii* shows that only 250 kWh are needed for DHW electric backup. This increase from 3.53 MWh/day (*Strategy i*) to 3.78 MWh/day (*Strategy ii*) corresponds to 63.1 kWh from ST backup and 185 kWh from HP backup, representing an overall increase of around 7%. In terms of daily dispatch costs, it is observed an increase of 8.5% since it represents an increase in the daily peaks (morning and evening), which forced the power plant to use a third working generator on that period.

When the ST backup is limited to off-peak hours, in *Strategy iii* and *Strategy iv*, there is an increase of 8.6% in energy demand, due to the imposition that the electric backup must be done until the tanks have enough thermal energy to assure the DHW demand of that day. However, in terms of peak load, *Strategy iii* has a higher impact since it turns all the ST systems at the same time, which will lead to larger dispatch costs (11% increase), while *Strategy iv* has similar dispatch costs to *Strategy ii*, since the load fulfills a longer off-peak period, leveling the dispatch of necessary generators to two generators only, although using higher generation costs. Overall, this shows that implementing demand response strategies using simple heuristics may increase the overall dispatch costs.

The last column presents the *Strategy v* which corresponds to demand response strategy described earlier in Section 4.2. A major increase in energy demand is observed (11.8%), since the model only looks to dispatch costs, and not to the amount of energy used - overall with this strategy, there is an excess of energy spent in “water heating” that may not correspond to reality. In any case, it presents the smallest increase on dispatch cost (only 5.2%), due to the stability of the load curve and the generation and dispatch costs are the same. This is explained by the fact the generation is optimized to have the same two generators permanently working, without the need to turn on/off another generator. This also configures a situation that may not correspond to reality, as there is the need to switch the generators for preventive maintenance purposes.

Table IV.6 - Comparative results of different strategies of demand response for a representative day, using only optimal economic dispatch

h	**i. Base load** [kW]	**ii. DHW at demand** [kW]	**iii. DHW off-peak midnight** [kW]	**iv. DHW off-peak disperse** [kW]	**v. Linear programming for demand < 170kW** [kW]
1	150.5	150.5	221.9	150.5	150.5
2	146.5	146.5	184.8	167.7	146.5
3	126.5	126.5	134.5	140.4	126.5
4	137.0	137.0	137.0	171.9	137.0
5	122.5	122.5	122.5	136.6	154.6
6	121.0	121.0	121.0	142.3	170.0
7	125.5	125.5	125.5	135.8	170.0
8	127.5	127.5	127.5	129.5	170.0
9	124.0	133.0	124.0	124.0	170.0
10	133.5	173.2	154.1	154.1	170.0
11	137.0	178.1	178.1	178.1	170.0
12	147.0	147.0	147.0	147.0	170.0
13	153.0	153.0	153.0	153.0	170.0
14	175.5	176.5	175.5	175.5	175.5
15	135.0	145.3	145.3	145.3	137.7
16	141.0	141.0	141.0	141.0	170.0
17	146.5	146.5	146.5	146.5	170.0
18	153.0	153.0	153.0	153.0	170.0
19	150.0	150.0	150.0	150.0	170.0
20	184.0	186.8	184.0	184.0	184.0
21	186.5	223.1	207.1	207.1	186.5
22	171.5	248.2	233.2	233.2	171.5
23	171.5	202.3	202.3	202.3	171.5
24	167.0	167.0	167.0	167.0	167.0
Total [MWh]	**3.53**	**3.78**	**3.84**	**3.84**	**3.95**
ΔMWh **[%]**	**-**	**7.0%**	**8.6%**	**8.6%**	**11.8%**
Gen. Costs [€]	**989.8**	**1058.7**	**1113**	**1109.5**	**1093.9**
Disp. Costs [€]	**1039.8**	**1128.7**	**1153**	**1129.5**	**1093.9**
Disp. Δ€ [%]	**-**	**8.5%**	**10.9%**	**8.6%**	**5.2%**

Indiscriminate DHW load | ST load | HP load | Best result | Worst result

5.2 Genetic algorithms with economic dispatch

With the introduction of genetic algorithms to randomly place the ST backup load along the day, two distinct formulations were used and compared:

a) a formulation based in the number of systems that are switched on at each hour, referred by models *GA_sys 1.0, 1.1, 2.0, 2.1*), where:
   - *GA_sys 1.0* and *GA_sys 1.1* assume the energy needs of 66 systems/day, at maximum power (that corresponds to minimum allowed energy needs, using this formulation), differing on the population size and number of generations (20/100 and 50/300, respectively);
   - *GA_sys 2.0* and *GA_sys 2.1* assume a need of 180 systems/day at maximum power (a scenario where there would be no contribution from solar gains), differing on the population size and number of generations (20/100 to 50/500, respectively).

b) a formulation in terms of energy (models *GA_E 3.0, 3.1, 3.2*), where is possible to define accurately the energy needs: for a representative day of low radiation, ST backup loads (63.05 kwh/day) are smaller than the installed capacity (152 kWh/day). The genetic algorithms were tested for population and generation sizes of 20/100, 50/200 and 100/300, respectively in *GA_E 3.0, 3.1, 3.2.*

For each case, the simulations were run five times in order to evaluate the robustness of algorithms. The simulations done in terms of systems have a standard deviation of around 0.3% of average value, and the ones done in amount of energy, less than 1.2%. The best results of each type were selected and presented in Table IV.7.

Comparing the first column of Table IV.7 (*Strategy ii*) and second column (*HP load*, totals 185 kWh/day, as mentioned previously in Section 5.1), is possible to conclude that, from the 8.5% increase on the dispatch costs in *Strategy ii*, 7.3% are due to the matching of HP load hours in the evening peak, being 1.2% from ST backup.

From the results of the number of systems formulation, represented by models *GA_sys 1.0, 1.1, 2.0* and *2.1*, is possible to observe that:

- the minimum energy needs that can be modeled, is equal to the nominal capacity installed (152 kW/day ST backup);
- when the DHW backup is added during the afternoon, to fulfill the valley between morning and evening peak, in *GA_sys 1.0* and *1.1*, the cost of dispatch has a 10.2% and 9.8% increase respectively;
- when the ST backup is also placed at the HP load hours, the dispatch cost increases considerably, having *GA_sys 2.0* and *2.1* a 17.7% and 17.2% increase respectively;
- with higher population size and number of iterations the model achieves better results (lower costs), justified by the fact that with higher diversity on population and along more generations, more feasible and adapted individuals are obtained, than with small populations with few generations.

Table IV.7 - Economic dispatch with genetic algorithms for DHW

h	**ii. DHW at demand** [kW]	**HP model** [kW]	**GA_sys 1.0** [kW]	**GA_sys 1.1** [kW]	**GA_sys 2.0** [kW]	**GA_sys 2.1** [kW]	**GA_E 3.0** [kW]	**GA_E 3.1** [kW]	**GA_E 3.2** [kW]
1	150.5	150.5	150.5	159.7	219.5	164.3	150.5	150.5	150.5
2	146.5	146.5	146.5	146.5	148.8	146.5	146.5	146.5	146.5
3	126.5	126.5	126.5	126.5	138.0	126.5	126.5	126.5	126.5
4	137.0	137.0	137.0	137.0	137.0	137.0	137.0	137.0	137.0
5	122.5	122.5	122.5	122.5	131.7	138.6	122.5	122.5	122.5
6	121.0	121.0	121.0	121.0	121.0	125.6	121.0	121.0	121.0
7	125.5	125.5	125.5	125.5	125.5	134.7	125.5	125.5	125.5
8	127.5	127.5	127.5	127.5	127.5	127.5	127.5	127.5	127.5
9	133.0	124.0	124.0	124.0	140.1	124.0	124.0	124.0	124.0
10	173.2	154.1	154.1	154.1	218.5	161.0	154.1	154.1	154.1
11	178.1	178.1	178.1	178.1	178.1	178.1	178.1	178.1	178.1
12	147.0	147.0	156.2	163.1	181.5	160.8	147.0	147.0	155.2
13	153.0	153.0	162.2	153.0	173.7	171.4	153.0	153.0	153.0
14	176.5	175.5	175.5	175.5	242.2	230.7	175.5	175.5	175.5
15	145.3	145.3	145.3	163.7	159.1	161.4	162.3	145.3	153.4
16	141.0	141.0	164.0	154.8	154.8	175.5	158.0	165.8	151.2
17	146.5	146.5	181.0	155.7	176.4	153.4	146.5	146.5	154.7
18	153.0	153.0	169.1	162.2	157.6	166.8	153.0	153.0	153.0
19	150.0	150.0	163.8	159.2	150.0	230.5	150.0	150.0	150.0
20	186.8	184.0	184.0	200.1	184.0	220.8	184.0	184.0	184.0
21	223.1	207.1	207.1	207.1	241.6	253.1	207.1	207.1	207.1
22	248.2	233.2	233.2	233.2	233.2	233.2	233.2	233.2	233.2
23	202.3	202.3	202.3	202.3	225.3	243.7	231.0	202.3	202.3
24	167.0	167.0	213.0	217.6	167.0	167.0	167.0	205.1	195.5
Total [MWh]	**3.78**	**3.72**	**3.87**	**3.87**	**4.13**	**4.13**	**3.78**	**3.78**	**3.78**
ΔMWh [%]	**7.0%**	**5.2 %**	**9.5 %**	**9.5 %**	**17.0 %**	**17.0 %**	**7.0 %**	**7.0 %**	**7.0 %**
Gen. Costs [€]	**1058.7**	**1045.8**	**1065.5**	**1062**	**1133.9**	**1128.3**	**1050.7**	**1050.1**	**1046.9**
Disp. Costs [€]	**1128.7**	**1115.8**	**1145.5**	**1142**	**1223.9**	**1218.3**	**1120.7**	**1130.1**	**1126.9**
Disp. Δ€ [%]	**8.5%**	**7.3 %**	**10.2 %**	**9.8 %**	**17.7 %**	**17.2 %**	**7.8 %**	**8.7 %**	**8.4 %**
Population Size	N/A	N/A	20	50	20	50	20	50	100
Generation	N/A	N/A	100	300	100	500	100	200	300
Formulation	N/A	N/A	nº of systems				energy		
Target	N/A	N/A	66 sys/day		180 sys/day		63.05 kWh/day		
Total Achieved	N/A	N/A	152 kWh/day		414 kWh/day		62.65	62.92	63.18
Details	BL+DHW	BL+HP	BL+HP+ST min		BL+HP+ST		BL+HP+ST		

Legend: Indiscriminate DHW load; ST load; HP load; Best result; Worst result

The results of amount of energy formulation, represented by models *GA_E 3.0, 3.1* and *3.2*, evidence that:

- it is possible to model scenarios with less backup needs, than the nominal ST capacity installed – on a representative day the ST backup needs are only 63.05 kWh/day, leading to 7% load increase, instead of 9.5%;

- in terms of costs, generating costs are lower for model *GA_E 3.2*, while model *GA_E 3.0* has the lowest dispatch costs – this can be justified by the fact that *GA_E 3.0* takes more advantage of the generators working in the peak period, making the transition for low demand periods smoother;
- Contrarily to what was observed in the *number of systems* formulation, the results do not improve with higher values of population size and number of iterations, which is reasonable given the infinite range of solutions in terms of amount of energy (in the number of systems formulation the range of solutions is limited as it uses integers).

Comparing the two formulations for GA (*number of systems* or *amount of energy*), and given the contribution of solar gains (which corresponds to the annual dynamic needs of electricity backup from season to season), the energy formulation is more accurate, since it is more sensitive to the fact that, in summer, backup needs are negligible; however, for constant daily demands, the formulation of number of systems can be simpler.

Analyzing the role of penalties in the GA optimization, penalties act as a filter, but not as a strict prohibition in the existence of certain chromosomes. In the model here described, the imposed penalties could always meet the total daily demand but failed frequently to distribute equally the demand by the three consumer's profiles.

Figure IV.7 and Table IV.8 compare the best result from Table IV.6 (*Strategy v*) and both formulations of nº of systems (*GA_sys 1.1*) and energy (*GA_E 3.0*), from Table IV.7. The best results are achieved with genetic algorithms optimization with the energy formulation (*GA_E 3.0*) since it is the model with better match between energy demand (1.8% increase to *HP model*) and less costs (0.5% increase to *HP model*). Although linear programming (*Strategy v*) demonstrates best daily dispatch costs, it presents two problems not reasonable in the long term: higher increase on total demand (12%/day) and exhaustive use of only two generators, not taking into account the wear caused to the generators.

Finally, the introduction of demand response strategy with GA optimization compared to DHW at demand (*Strategy ii*), presents for the best result (*GA_E 3.0*):

- 1% savings in dispatch costs (8€/day, 12 920 €/year);
- 40 kg CO_2 emissions per day, 14 ton of CO_2 emissions per year[1]

Table IV.8 - Quantitative comparison of best models with different formulations

	Base load	**HP model**	**Linprog <170kW**	**GA_sys 1.1**	**GA_E 3.0**
Total [MWh]	3.53	3.72	3.95	3.87	3.78
ΔMWh to base load [%]	-	5.2 %	11.8%	9.5%	7.0%
Generating costs [€]	989.8	1058.7	1093.9	1062	1050.7
Dispatch costs [€]	1039.8	1115.8	1093.9	1142.0	1120.7
Δ€ to base load [%]	-	7.3 %	5.2 %	9.8 %	7.8 %

[1] Converting generating costs to liters of consumed diesel with 0.54 €/l and assuming 2.68 kg CO_2/ l of consumed diesel

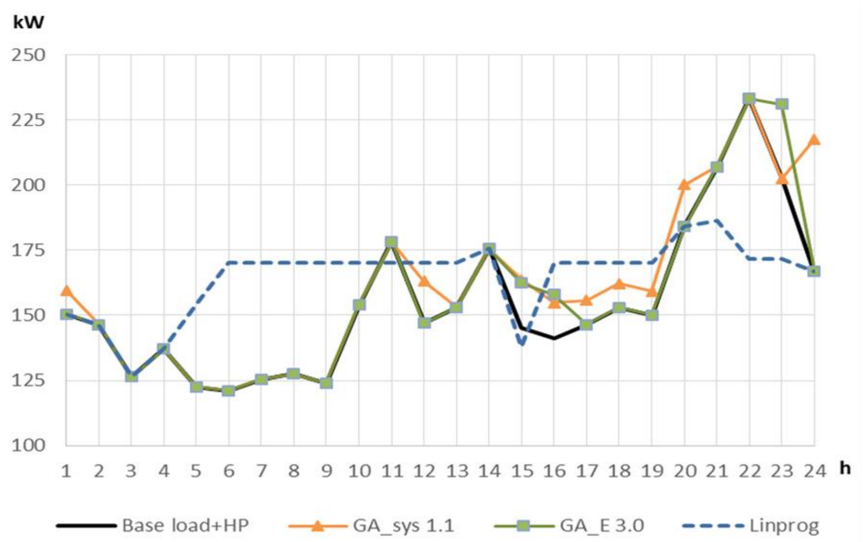

Figure IV.7 - Qualitative comparison of best daily models with different formulations

6 Conclusions

This work provided the possibility to test and prove the efficiency of genetic algorithms as an optimization tool to implement demand response from the grid operator perspective and minimize the dispatch costs of a small isolated grid, when integrating renewable technologies backup on the grid.

Comparing the different demand response strategies, using heuristics and linear programming, it was found that the one that minimizes the daily operation costs is the linear programming model, although it presents the highest increase in energy demand. In terms of demand response based on genetic algorithms, it was found that the highest increase in the daily operation costs is due to heat pumps that alone represent a 5.2% increase when compared to base load. It was also observed that when ST backup is placed at the same hours of HP backup, the costs increase. However, if the ST load is distributed across the off-peak hours, the overall costs decrease when compared to *at demand* strategy. The *GA_E 3.0* model presents the best result, with a 1% decrease compared to the *at demand* model. Tracking these results for different population sizes and generations, it is observable that for the number of systems formulation, better dispatch operation is achieved with more generations, validating that, electric dispatch coupled with demand response, is more suitable to minimize costs with genetic algorithms. Also the formulation on genetic algorithms is a scalable formulation that can fit different case-studies.

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Chapter V
Demand response modeling: a comparison between tools

Abstract

The potential to reschedule part of the electricity demand in energy systems is seen as a significant opportunity to improve the efficiency of the systems, especially on remote and isolated systems. From the supply point of view, that flexibility might bring significant improvements to the generation dispatch, especially when in the presence of renewable resources; from the demand point of view, that flexibility could allow customers to benefit from reducing their energy bills. To study these types of implications, modeling tools have been introducing the possibility to include flexible loads on the optimization process, although some use very simplified methodologies to do it. This study compares how different modeling tools consider fixed and flexible loads in the dispatch optimization, analyzing their different strategies. Three different scenarios were simulated in HOMER, EnergyPLAN and an economic dispatch self-built model in *MATLAB*, using as case study the Corvo Island, Portugal. The comparison results indicate that HOMER and EnergyPLAN still assume that flexible loads are a second priority load that are met in off-peak hours or in the presence of excess electricity from renewable sources, not taking directly into account the economic impact of such decision. On the other hand, the self-built model that is more flexible on the optimization approach is the more close to the actual operation and presents the best savings when using demand response strategies, albeit representing only a 0.3% decrease in the operation costs. We conclude that the modeling tools should evolve and refine their optimization strategies to capture the total benefits of using demand response to improve energy systems performance.

Keywords

Economic dispatch; HOMER; EnergyPLAN; Renewable energy; Demand response; Flexible load

1 Introduction

The ability to reschedule part of the daily electricity load is expected to lead to a decrease of the dispatch costs of the electricity generation systems. The accurate understanding of available resources and, in case of renewables, their dynamics, matching the installed capacities with investment and operating costs, creates new opportunities to improve economic dispatch through the implementation of demand response programs. Demand response can be defined by a voluntary and temporary adjustment of power demand taken by the end-user as a response to a price signal, or taken by a counter-party, like the utility, based on an agreement with the end-user [1]. Therefore, demand response might have a pivotal role on the future planning of smart grids, making them more cost effective and supporting the balance between supply and demand [2][3]. However, modeling the impact of demand response strategies, especially on remote and/or isolated systems, is a challenge to current energy modeling software. One of the main obstacles is the time resolution: long term is useful for projecting and optimizing investments on energy systems, but there is actually the need for a more refined time resolution in order to have a realistic, efficient and reliable system operation [4].

With that in mind, many authors [4][5][6][7] have focused on assessing strategies that use and combine different time resolutions, from long term investment strategy to short-term optimization of generation dispatch. If on one hand, when considering a long term horizon there is the need to decide on which capacity and type of energy supply the investments should be made to respond to a certain electricity demand and growth; on the other hand, there is also the need to be able to model different energy suppliers and loads, preferably using higher time resolutions. The combination of the two time resolutions will help the achievement of an optimal economic dispatch with less operation costs, losses or, in case of renewable integration, no excess of generation capacity.

Managing correctly all the grid variables between demand and supply, becomes more crucial when dealing with isolated microgrids, such as islands, where we need to assure reliable and self-sustainable energy systems, preferably reducing fossil fuel imports to the island, and consequently the associated CO_2 emissions, and having an efficient energy use on the demand side [8].

There are several modeling tools available as reviewed by [9], with HOMER [10] being the most used for modeling microgrids, and EnergyPLAN [11] normally used for larger systems, particularly at the regional level. Although they are popular and include flexible load options that can be used to model demand response actions, there is a gap on studying what is their approach to model it, the impacts it has on the modeling of the system and its main limitations. Demand response modeling has driven a lot of studies lately, but the main denominator is that each one develops its one algorithm, instead of using the available modeling tools. For instance in [12] and [13] demand response models that aggregate residential appliances are developed; in [14] and [15] different DR frameworks to accommodate electric vehicles are proposed; in [4], [16], [17] the potential of DR models to integrate renewable resources is studied and developed; and from the grid operation point of view, [18], [19], [20] reveal the technical and economic impact of DR programs at regional grid-level, trough self-built models. In [21] a self-built model is also presented to model virtual power plants as DR agents in grids with decentralized energy resources. Therefore, most studies on flexible loads are based on self-built models instead of using some of the most used modeling tools.

This paper uses the case study of the island of Corvo, a small and isolated island in the mid-Atlantic Ocean, where recently the Municipality has installed electric domestic hot water systems, consisting of heat pumps and solar thermal collectors to offset the gas consumption. This has introduced an additional electric load that needs to be managed in order to avoid negative impacts, like peak increases [22]. For that purpose, the possibility of installing load controllers in each system in order optimize the electricity supply, by rescheduling the DHW systems, is currently under consideration [23], however no DR system has been deployed in the island yet.

This paper compares the HOMER and EnergyPLAN modelling tools, with a newly self-built economic dispatch model [23], exploring the advantages and limitations of each tool using demand response strategies in Corvo Island. The self-built economic dispatch model used in this paper introduces technical constraints from the generation and distribution network [24] and optimizes the reschedule of demand response through genetic algorithms, as described in [23].

Overall, there is a lack of knowledge on why the most used modeling tools are not typically considered for modeling flexible loads. As such, the scientific contributions of this paper are:

- Assessment of the impact of aggregating individual DHW backup loads as manageable flexible loads, using genetic algorithms to optimize its placement in an innovative self-built model;
- Comparison of the results obtained with the self-built and some of the most used modeling tools (HOMER and EnergyPLAN), by assessing how they optimize flexible loads and its impacts;
- Presentation of recommendations for improving the modeling of flexible demand in existing tools, to enable them to perform a wider variety of studies.

The paper is organized as follows. Section 2, describes the importance of modeling microgrids and the problem of demand response, and introduces the modeling tools that are used in this paper. In Section 3, the Corvo Island case study is presented. Section 4 describes the different scenarios that are modeled and in Section 5, the results are presented and discussed. Section 6 makes the final statements of the work.

2 Modeling microgrids and demand response

With the increase of distributed generation, microgrids are becoming more viable. The vision of having power grids that can be composed of many microgrids that can also operate on an islanded mode, brings new challenges and opportunities [25]. However, in isolated systems (physically or not) small changes on the electricity grid (either on the demand or supply side) may lead to large impacts that have to be prevented.

The interest on studying the impacts of demand response is growing, especially on domestic demands, where detailed studies are arising. The potential of domestic sector is huge: for example in [26], the authors present a high resolution model for identifying potential flexible loads; in [27][28] the potential from mixed thermal needs is analyzed, like heating/cooling [29], DHW needs [23], and large electric consuming appliances [13][30]. In [12] a similar approach to our study is developed, with the aggregation of air conditioning systems as demand response loads of 900 houses. The industrial sector is also a promising target [31], which is normally considered within regional-scale approaches, like in [32], where an extensive assessment of the potential of flexible loads in a future energy scenario in Denmark is presented, or in [33] where a more theoretical approach to flexible loads from the electricity pricing markets point of view is performed.

2.1 Software modeling tools

There are several modeling tools able to optimize energy systems that integrate renewable energy (listed and compared in [9]) and eventually to optimize some kind of demand response approach.

In [8], a list of studies of hybrid renewable energy system analysis on isolated microgrids is presented, where some case studies use modeling tools as system optimization method. HOMER is the most referenced tool, and there are several studies that use it for that purpose: in [34] a case study demonstrates the use of HOMER to design a renewable polygeneration energy container in order to provide energy in remote regions, and in [35] HOMER is used for deciding which renewable energy system scenario is more suitable for making Karpathos Island, in Greece, a self-sustainable island. There are already some examples of using HOMER's demand response options: in [36] HOMER is used coupled with another framework, in order to incorporate more technical constraints on the modeling of an isolated microgrid; in [37] a water treatment plant is used as DR tested on isolated and connected microgrid; and in [17] a biomass gasification plant is modeled as DR to improve renewable energy penetration.

EnergyPLAN is also a very popular tool to design large energy systems for countries or regional grids, like in [38], where the tool was used to analyze the integration of multiple renewable capacities in Denmark. However, it has also been used in smaller systems like in [39], where the tool was applied to evaluate the energy system of the small island of Mjlet, in Croatia, presenting successful comparative results. Still, these case studies do not address demand response.

As stated previously, other models that deal specifically with DR are being developed by different research teams in order to fill the gap left by the most used modeling tools. Some examples are DER-CAM [40], which is a complex model for modeling microgrids and that has already some demand response options [41][42], or the mix model developed in [15] where the authors combine TIMES [43] and mixed integer programing in order to complement the optimization with medium and short-term time horizon to assess demand response using electric vehicles (EV).

2.1.1 HOMER Energy

HOMER Energy [10] is a microgrid modeling tool that is targeted for the economic optimization of isolated or grid-connected hybrid renewable energy systems [9]. It provides multiple pre-determined choices between different types of energy generators, which can be specified in detail. It also includes some storage options (batteries, hydrogen or flywheels). There is the possibility to include operation, maintenance and replacement costs of the different technologies, but it is not possible to include other important operational constraints like start up/shut down costs of diesel generators. The time resolution of the model can go from one day to one year, based on a default time step of one hour (but that can be tuned, from one minute to several hours). The optimization of the system is made in economic terms, listing all the feasible configurations with increasing Net Present Cost (NPC).

To model demand response, there is the choice to define a percentage of the total load that can be deferrable, specifying the time lapse in which the demand needs to occur (average daily deferrable load for each month, and maximum peak load). Fixed loads on HOMER dispatch strategies have always priority over flexible loads and storage. The strategies in HOMER to meet the flexible loads, can be one of the following two:

- The load following strategy: the flexible loads or the charging of the storage bank (batteries) are met only when there is excess of electricity (normally from renewable sources);
- The cycle charging strategy: the flexible load is met whenever a generator is operating lower than full capacity.

2.1.2 EnergyPLAN

EnergyPLAN [11] is a national and regional grid modeling tool for planning energy supply strategies [9], where a special focus on heat and electricity demand is given. The user can choose the installed capacity of energy generation and storage technologies, specifying fuels and average system efficiencies. The optimization can be technical or economic and the time resolution used is annual, based on an hourly time step. It is not possible to include detailed technical data, like start up/shut down costs, albeit operation, maintenance and investment costs can be defined.

To model demand response, there is the possibility of defining an amount of flexible load (energy and power) and in which time lapse does the demand need to occur (monthly, weekly, daily). Flexible demand is scheduled according to the electricity supply and demand situation, placing it where the gap between working capacity and demand is higher, like off-peak hours and hours with excess of electricity. A detailed description of modeling flexible loads in EnergyPLAN is presented in [32].

EnergyPLAN also provides other possibilities to model DR approaches: one is related to the battery charging of electric vehicles, through the smart charging approach; another possibility sector is to consider individual heat pump systems for heat generation as flexible loads that can be used to manage critical excessive production. However, for demand response purposes in this case study, only the ST backup needs were considered as flexible loads, given the little flexibility of HP highlighted by other authors [29]. Thus, for a question of normalization among tools and adequacy for the approach taken, the use of DR in EnergyPLAN is done considering the general algorithm for undifferentiated flexible loads.

2.1.3 Self-built economic dispatch model (ED model)

This new self-built model recently developed, described in [23] and [24], is a daily economic dispatch model that combines the unit commitment problem and a linear dispatch method, taking into account operational restrictions of various types for the generating technologies, such as start-up and shut-down costs, minimum up and down time, ramp up/down rate, minimum power output and operating reserve. The model works with an hourly time-step, calculating for each hour the generation and dispatch costs. Demand response is introduced by a genetic algorithms optimization approach that minimizes the daily dispatch cost, through the optimized placement of solar thermal backup along the day.

3 The Corvo Island case study

Corvo Island is the most western, smallest and isolated island of the Azores archipelago, in the middle of the Atlantic Ocean. Corvo has only 17 km^2 and has 430 inhabitants living in 144 houses [44]. Due to remoteness and high costs of imports to the island, the Regional Government of Azores together with the local utility, Electricity of Azores [45], has implemented some projects (e.g. the Domestic Hot Water supply using solar thermal systems and heat pumps) and conducted studies (renewable electricity from wind and storage from water pumping) that are currently undergoing, in order to make the island energy systems more sustainable.

3.1 Characterization of electricity system

The electric system of Corvo Island is based on a diesel power plant of four generators with a total installed capacity of 536 kW, which results in a 100% external dependency from fossil fuels [45]. Recent improvements have been made in the supply of domestic hot water, with the replacement of the previous gas boilers systems by 66 solar thermal systems and 78 heat pumps. This improvement has been a step forward to the island energy autonomy, by assuring the continuous supply of hot water that, in the past, suffered from periodic shortcoming when the supply of liquefied petroleum gas to the island was interrupted under severe climatic conditions [22].

The annual load of the island, prior to the electrification of DHW, was around 1.4 GWh with a daily peak of 225 kW and a daily consumption of 3.83 MWh/day. In Figure V.1, an annual average of the daily load of Corvo Island is presented, as well as a typical winter and summer day. The thermal power plant of Corvo operates with a reserve operation of 20% of the load, and Table V.1 describes the specifications of the diesel generators that are part of the electric system of Corvo Island.

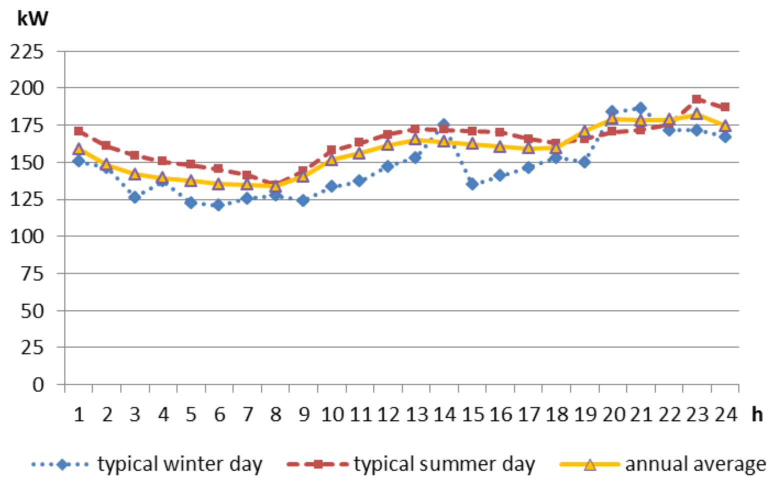

Figure V.1 - Typical daily load diagram for Corvo Island, still without DHW electrification loads (2012)

Table V.1 - Diesel Generators specification data

Generators		#1	#2	#3	#4
Pnom - Nominal Power [kW]		108		160	
Fuel Consumption [l/h]	100% Pnom	31.2		49.4	
	75% Pnom	24.2		37.4	
	50% Pnom	17.4		25.6	
Start-up cost (cold/hot) [€]		20/0		30/0	
Minimum power output [kW] (% of Pnom)		42 (39%)		64 (40%)	

Based on the fuel consumption data described in Table V.1, two equations that describe the fuel consumption of each generator according to its power output were computed. Equation V.1 describes the fuel consumption curve for Generator #1 and #2 and Equation V.2 for Generator #3 and #4:

$$y_{gen\ 1;2}\ (x) = 0.2556x + 3.5667 \qquad \text{(V.1)}$$

$$y_{gen\ 3;4}(x) = 0.2975x + 1.7667 \qquad \text{(V.2)}$$

where $y_{gen\ i}$ is the diesel consumption in [l/h] of the generator i and x is the power output in [kW].

Considering an energy content of diesel of 36.25 MJ/l, the partial load efficiencies were calculated according to Equation V.3 and are presented on Table V.2

$$Eff = \frac{1}{\frac{y_{gen\ i}(0.75\times P_{nom})}{0.75\times P_{nom}}\times\frac{36.25}{3.6}}\ [\%] \qquad \text{(V.3)}$$

Table V.2 - Partial load efficiencies for Generators #1 & #2 and #3 & #4

Generators		#1 & #2	#3 & #4
Partial load efficiency [%]	100% Pnom	34.41	32.19
	75% Pnom	33.14	31.81
	50% Pnom	30.87	31.07

The average efficiency was considered to be at an operation point of to 75% of the nominal power, being 33.14% for generator #1 & #2 and 31.81% for generator #3 & #4.

3.2 Characterization of domestic hot water system

With the implementation of a new DHW system (solar thermal with electricity backup and heat pumps), there is an opportunity to reschedule part of DHW electric backup to periods that optimize the economic dispatch of the power generation. The total electrification of DHW is expected to increase the overall annual electricity demand by 7% and the annual peak load by 50% [22]. In order to avoid such dramatic impact and consequently the need to invest in further capacity, a demand response strategy should be adopted.

For that purpose, and since heat pumps have a limited flexibility to act as demand response agents [29], we calculated the electric backup needs of the solar thermal systems taking into account the island solar resource, provided by NASA [46], represented in Figure V.2. Since the models consider annual averages, an average day was used as reference scenario, and the corresponding DHW expected loads are presented in Table V.3. Still, as the implementation of the DHW systems is very recent, there is no available operation data.

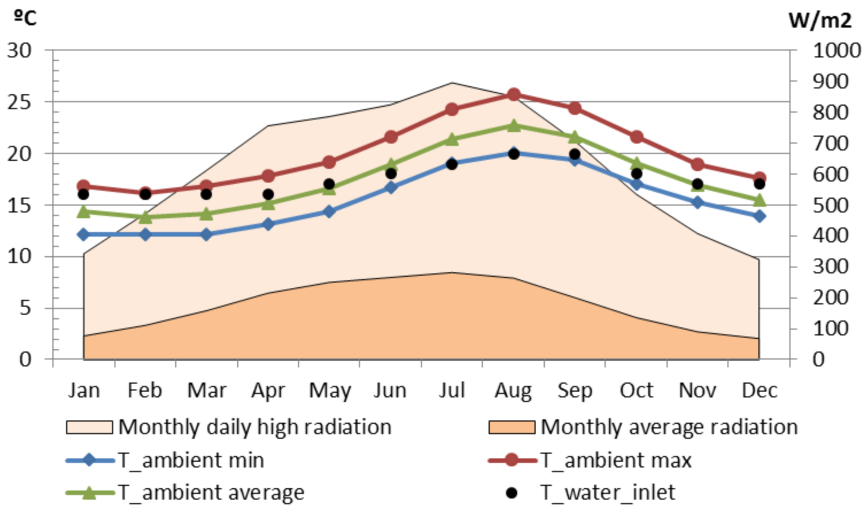

Figure V.2 - Monthly horizontal global radiation on Corvo Island, and ambient and water inlet temperature, represented by *T_ambient* and *T_ water_inlet,* respectively

Table V.3 - Expected loads for an average day

Average day base load	**DHW backup needs**	
	HP	ST
[MWh/day]	[kWh/day]	[kWh/day]
3.53	185 (5.2%)	63.1 (1.8%)

Currently, in what concerns electricity supply, Corvo Island is still 100% diesel dependent, but the implementation of renewable electricity suppliers is being studied. Although no demand response system has been implemented in the island yet, the possibility of having a DR system in this mini-grid might increase the penetration of renewable energy sources such as wind, the most common in islands.

4 Scenarios

The modeling of demand response on different software can be significantly different, as each tool has its own different specifications of the input and output data. For the used modeling tools used, Table IV.4 compares the specifications of each case.

Table V.4 - Software modeling tools summary

	Electricity Demand				**Supply**		**Dispatch**	
	Fixed	Flexible	Reschedule method	Flex. Load Time frame	Technology	Definitions	Method	Time resolution
HOMER	Total load	% of the given load	• Load following method: reschedules for hours with excess of electricity • Cycle charging: reschedules when a generator is operating under its nominal capacity	Daily according to month of the year	List of pre-defined technologies	Capacity, efficiency curve, minimum output power for each generator individually	Economic	Hourly (default) with year-horizon
Energy PLAN	Base load	Additional amount of energy (general or associated with EV or HP)	Reschedules, normally for off-peak or for hours with excess electricity	• Daily • Weekly • Monthly	List of pre-defined technologies	Capacity and efficiency for each type of technology	Technical / Economic	Hourly with year-horizon
ED model	Base load	Additional amount of energy	Reschedules with genetic algorithms, optimizing the economic dispatch	Hourly	Can be defined for any technology	Capacity, efficiency and all technical constraints for each generator can be introduced	Economic	Hourly with daily-horizon

To enable the comparison, it was decided to model one annual average day (Table V.3) with an hourly time step, and three scenarios were designed, as systemized in Table V.5:

- The first scenario models only the base load prior to the installations of the DHW systems: it intends to compare the tools with the actual operation provided by Electricity of Azores, and to identify the largest differences in the decisions of system dispatch. There is also the possibility to compare which of the tools validates best with actual operation;

- The second scenario aims to test how the tools respond to a fixed increase on the load, and consequently what is the estimated peak load, due to the installation of DHW systems;

- The third scenario intends to compare the inclusion of a certain flexible daily load that has to be fulfilled within the day, using the demand response strategies of each tool, to study how they differ and can be improved; DR is applied on a day-ahead-basis to allow the utility to plan where DHW backup loads can best suit the daily dispatch.

Table V.5 - Scenarios taken into account

	Fixed load	Flexible load	Description of the model
Scenario 1	Base load	No	Model only the dispatch of the base load
Scenario 2	Base load + fixed DHW backup needs	No	Model the base load with the additional load from DHW backup at the time it is needed
Scenario 3	Base load + Heat pumps load	Solar thermal backup load	Model the base load with the fixed heat pumps load and the flexibility to reschedule the ST backup load

While HOMER and the ED Model provide the possibility to model individually each generator, through the definition of the nominal power, efficiency curve, minimum power output (as described earlier in Table V.1 and Equations V.1 and V.2), EnergyPLAN only allows to describe the general technology, such as the diesel power plant capacity, and average efficiency. In order to be able to compare both tools, the four generators were aggregated in two groups of generators, with the same capacity: the small ones (#1 & #2) with 108 kW each, 216 kW aggregated, and the big ones (#3 & #4), with 160 kW each, 320 kW aggregated capacity, inserted on PP1 and PP2, respectively. Average efficiencies were used in EnergyPLAN, for each group of generators, according to Equation V.3 and Table V.2. An economical optimization strategy was chosen in both modeling tools, using 0.6935 €/liters as fuel price.

5 Results and Discussion

5.1 Scenario 1 – Modeling base load

Figure V.3 presents the dispatch of each generator for the different modeling tools and the real operation data, for a typical day.

Regarding the use of the different generators, it is possible to see in Figure V.3 that:

- In the actual operation, there are always two generators of different capacities (108 kW and 160 kW nominal capacity) committed to assure the load and the reserve: the small generator #1 is always working approximately at 54% of its capacity, combined with #3 during the day (56%) and with #4 in the off-peak hours (46%), to impose some rotation between the generators to increase their reliability. Generator #2 is the stand-by generator that is committed (at 27% capacity) on the evening peak load, below its minimum power output constraint (38.9 %);

- When using HOMER, the production in off-peak hours (3h and 5h-9h) is made through one large generator (#3) at approximately 78% of its capacity. This does not satisfy the usual strategy of running a power plant with *n-1* redundancy. During the day and peak hours (10h-2h) it chooses to commit two small generators (#1 and #2), at approximately 100% and 50% average capacity, respectively. Generator #4 is never committed;

- EnergyPLAN opts to use the aggregated small generators #1 & #2, 24h/day, to meet all the demand, since they have a higher efficiency than the aggregated big generators;

- The economic dispatch model (ED model) uses one small generator (#1) all day at 67% of its capacity, together with generator #2 at 66% during off-peak hours, and generator #3 during the day and in evening/night at 50%.Generator #4 is never committed. The main difference to the Actual Operation is that during off-peak hours there are 2 small generators working instead of a mix combination, and that is due to the higher efficiency of the smaller generators.

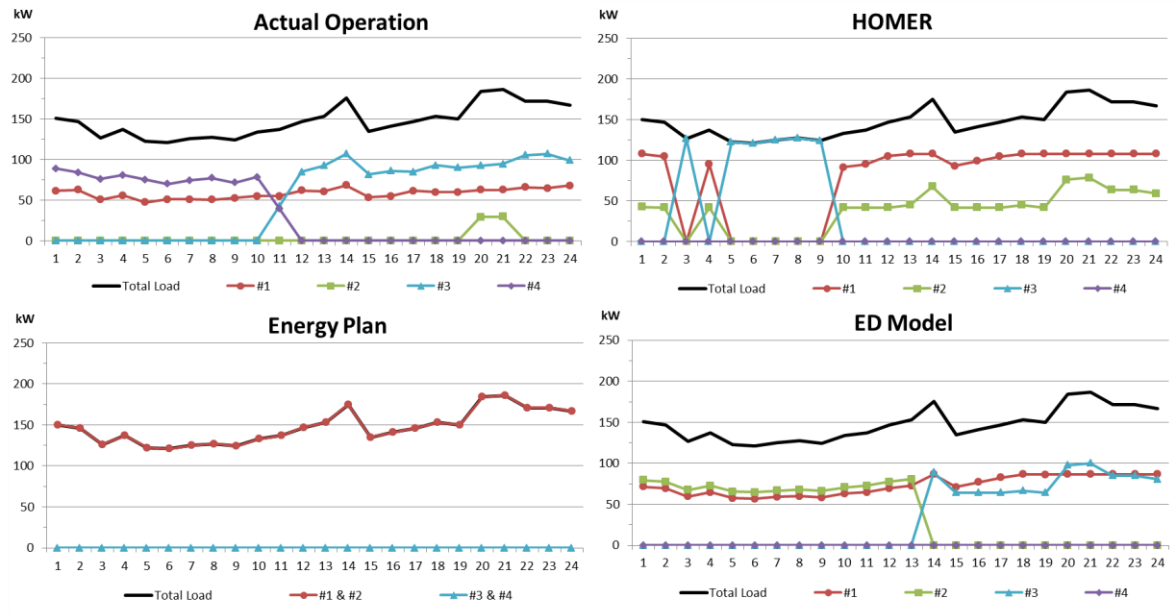

Figure V.3 - Scenario 1 comparison of committed generators, for the actual operation and different modeling tools

Comparing the different models, the ED model proposes a solution closer to the actual operation than the other tools, with two generators always committed between 50% and 70% of their capacity. HOMER and EnergyPLAN push the working generators to work at 100% of their capacity without reserve and, in the case of HOMER, the generators switch on and off for short periods of time. They also do not take into consideration the turnover between working generators. The ED model takes into consideration both technical and reliability constrains that are also taken into account in actual operation (minimum power output, minimum up/ down time, ramp up/down rate, start-up/shut-down costs, etc.), which translates into a similar operation.

Table V.6 presents a comparison of the working hours of each generator for the different models, with the exception of EnergyPLAN, where the values correspond to aggregated small (#1 & #2) and big generators (#3 & #4). It is possible to observe that only HOMER opts for not having an all-day working generator, unlike the rest of the models. The actual operation runs in general one small and one big generator, while HOMER, EnergyPLAN and ED model use mainly the two small generators, since they are more efficient.

Table V.6 - Percentage of working hours and average capacity during a day, for Scenario 1, or each generator

	# 1		# 2		# 3		# 4	
	% of working hours	Working average capacity	% of working hours	Working average capacity	% of working hours	Working average capacity	% of working hours	Working average capacity
Actual Operation	100 %	54 %	8 %	27 %	58 %	56%	46 %	46%
HOMER	75 %	96 %	75 %	47 %	25 %	78 %	0 %	-
Energy PLAN	100 %			68 %	0 %			-
ED Model	100%	67 %	54 %	66 %	46 %	49 %	0 %	-

5.2 Scenario 2 – Modeling base load with fixed additional load

The results obtained for Scenario 2 are presented in Figure V.4. As with the previous scenario, none of the three modeling tools used generator #4.

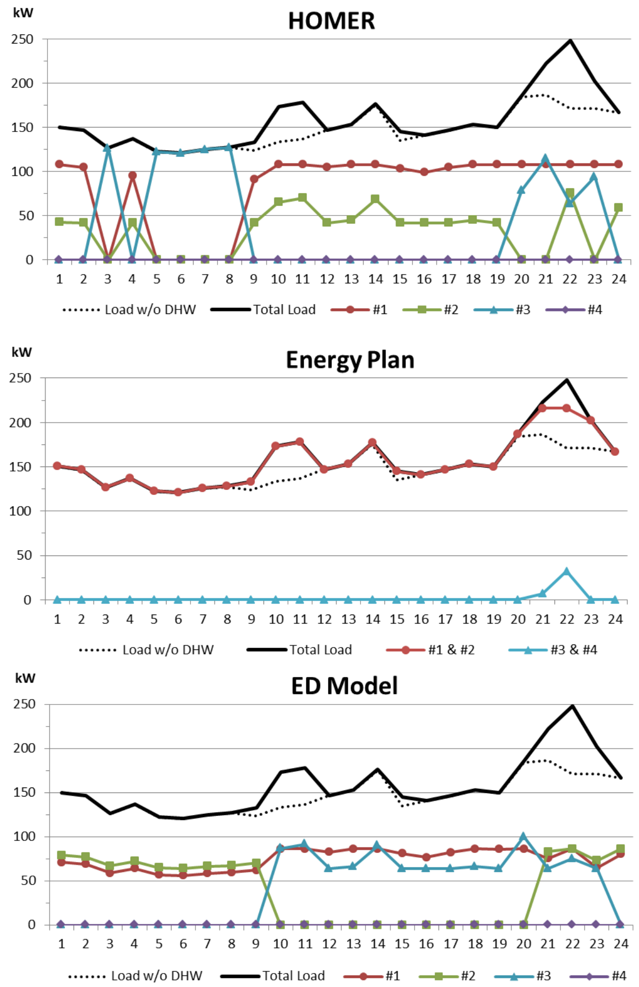

Figure V.4 - Scenario 2 comparison of committed generators between different modeling tools

When compared to Scenario 1, there is an increase on total load and peak load, due to the implementation of the electrified DHW systems. Analyzing each modeling tool, it can be seen that:

- HOMER continues to switch *on* and *off* the generators for very small periods, and generator #3 works alone in some of the off-peak hours at around 80% of his capacity and at 55% of its capacity in the evening peak. The smaller generators #1 and #2 are used during the rest of the day, at the same time, at 97% and 47%, respectively;
- EnergyPLAN continues to use aggregated generators #1 & #2 at 72% capacity, using only the aggregated #3 & #4 generators to cover the evening peak, only at 6% of their capacity;
- The ED Model uses all three generators, but alternates much less between them than HOMER: Generators #1 and #2 assure the off-peak hours at 58% and 65% of their capacity, and generators #1 and #3 assure the rest of the day at 76% and 46% of their capacity. In the evening peak, to respond to the increase in load, generator #2 is also committed at 76%.

When comparing these results to Scenario 1, Table V.7 shows that EnergyPLAN continues to have the same pattern of generator use, while the HOMER and the ED Model start to use more generator #3. Furthermore, the ED Model makes generator #3 the second most used generator, as occurs in the Actual Operation for Scenario 1.

Table V.7 - Percentage of working hours and average capacity during a day, for Scenario 2, for each generator

	# 1		# 2		# 3		# 4	
	% of working hours	Working average capacity	% of working hours	Working average capacity	% of working hours	Working average capacity	% of working hours	Working average capacity
HOMER	79 %	97 %	67 %	47 %	38 %	68 %	0 %	-
Energy PLAN	100 %			72 %	8 %			6 %
ED Model	100 %	76 %	54 %	76 %	58 %	46 %	0 %	-

5.3 Scenario 3 – Modeling base load with flexible additional load

As defined in Table V.3, the flexible load to be allocated is 63.1 kWh/day and Figure V.5 compares the results obtained by the different modeling tools for Scenario 3, in which the demand response of the DHW backup is considered. As in the previous scenario, no tool used generator #4.

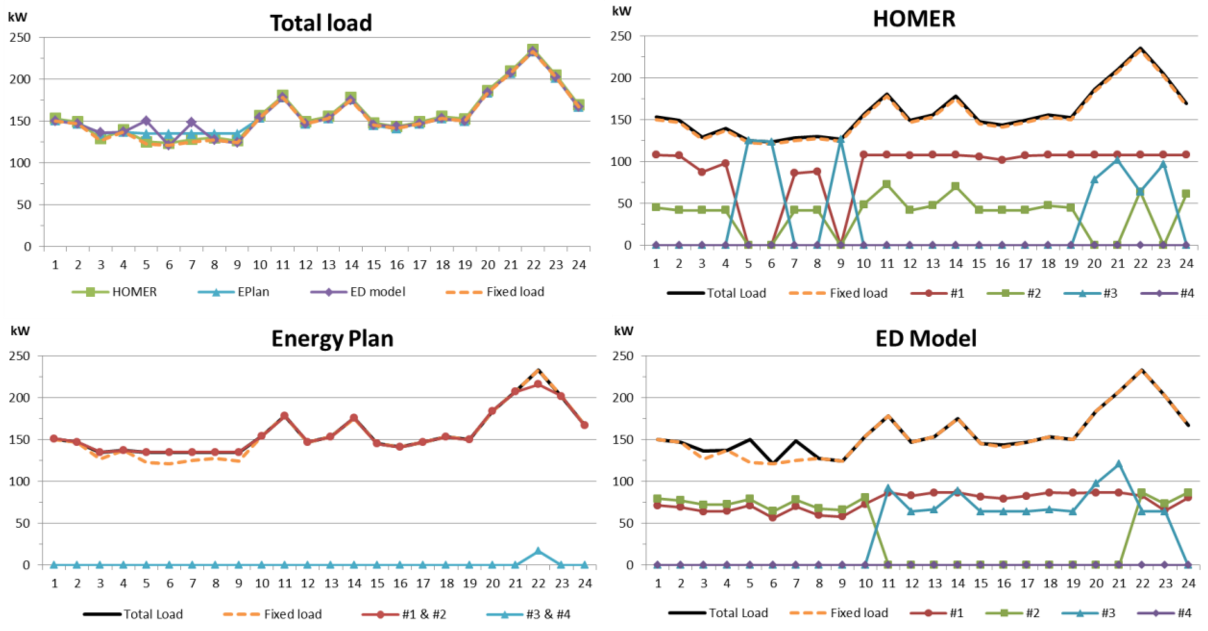

Figure V.5 - Comparison of Scenario 3 between different modeling tools

It is observed in Figure V.5 that:

- HOMER opted for the cycle charging dispatch strategy (see description in Table V.4), by scheduling the flexible load uniformly at each hour of the day (in average 2.62 kW), and the generators were used in the same logic as in Scenario 2; the total allocated flexible load was 62.99 kWh/day;

- In EnergyPLAN the flexible load is positioned at off-peak hours, where the gap between the load and nominal committed power is higher, with the aggregated generators #1 & #2 supporting that increase (3h and 5h-9h); the total allocated flexible load was 64 kWh/day;

- In the ED model, the flexible load is placed in the majority in the off-peak hours (3h,5h, 7h) and some little backup in the afternoon (15h-16h) to store enough thermal energy for the evening peak; in the off-peak, the flexible load takes advantage of having committed the two generators more efficient (#1 and #2) at an average load of 60% and 68%; during the rest of day the model chooses to commit one small (at 77% average power) and one large generator (at 44% average power) assuring an operating reserve of 20% of the load and avoiding the shut-down/start-up costs of switching off and on other generators in between peaks. the total allocated flexible load was 63.26 kWh/day;

Table V.8 shows that for HOMER there is an increase of the working hours of generators #1 and #2 while the power committed decrease (since the load is more leveled along the day than in Scenario 2). For EnergyPLAN the aggregated generators #1 & #2 present a 1% increase in the power committed at the same time the aggregated generators #3 & #4 have a decrease in the working hours and power committed (4% and 1%, respectively to Scenario 2). The introduction of flexible demand on ED model results in a decrease of 6% of the average power committed for generator #1 and #2 – as there is no need to cover high peaks, and a decrease of working hours for generator #3 (less efficient) with a 1% increase in the power committed.

Table V.8 - Percentage of working hours and average capacity during a day, for Scenario 3, for each generator

	# 1		# 2		# 3		# 4	
	% of working hours	Working average capacity	% of working hours	Working average capacity	% of working hours	Working average capacity	% of working hours	Working average capacity
HOMER	88 %	96 %	75 %	45 %	29 %	64 %	0 %	-
Energy PLAN	100 %			73 %	4 %			5 %
ED Model	100 %	70 %	54 %	70 %	54 %	47 %	0 %	-

5.4 Discussion

Table V.9 presents the estimated consumption of liters of diesel by each tool in each scenario and Table V.10 summarizes the daily dispatch costs for the different modeling tools. Costs related to distribution losses were not considered, as they would be the same for every model and no additional value for the comparison would be added.

Table V.9 - Comparison of liters of diesel consumed per day for different scenarios and modeling tools

	Actual Operation	**HOMER**	**EnergyPLAN**	**ED Model**
	[l/day]	[l/day]	[l/day]	[l/day]
Scenario 1	1161.57	1076.19	1056.81	1090.48
Scenario 2	-	1147.99	1134.44	1166.11
Scenario 3	-	1147.88	1133.56	1162.49

Table V.10 - Comparison of operational costs for different scenarios and modeling tools

	Actual Operation	**HOMER**	**EnergyPLAN**	**ED Model**
	[€/day]	[€/day]	[€/day]	[€/day]
Scenario 1	805.55	746.34	734.97	786.25
Scenario 2	-	796.13	786.73	858.70
Scenario 3	-	796.05	786.12	856.19

For Scenario 1, ED model presents only less 2.4% than the Actual Operation costs even consuming different amounts of diesel (ED model consumes 6.1% less). Both HOMER and EnergyPLAN present lower diesel consumption (7.4% and 9% reduction compared to Actual Operation, respectively) and similar reduction in costs (7.4% and 8.8%, respectively). That is justified by the fact that the ED model and the Actual Operation account for start-up/shut-down costs of the generators, while HOMER and EnergyPLAN do not.

In Scenario 2, it is observed that HOMER and EnergyPLAN present significantly lower operation costs and less consumption of liters of diesel. While in terms of liters of diesel consumed they present less 1.6% and 2.7% than the ED model, respectively, in terms of costs they also estimate less 7.3% and 8.4%

than in the ED model. This difference between HOMER and EnergyPLAN can be explained by the fact that HOMER commits generator #3 during more time (Table V.7, 38%), which is less efficient, than EnergyPLAN (8% of the working hours).

For Scenario 3, HOMER and EnergyPLAN present almost the same operation costs and diesel consumed than the ones they presented each for Scenario 2, with only a decimal decrease. This is due to the way these tools consider demand response: they do not differentiate in terms of costs the instant in which the demand is placed, since they are more prepared to optimize accurately demand response in presence of excess of energy (normally from renewables) or storage technologies:

- In HOMER, and in the absence of renewable sources or storage technologies, the dispatch strategy is the cycle charging, resulting on an equal distribution of the flexible load for each hour of the day, but still, the diesel consumption and operation costs are residually lower than in Scenario 2 (less 0.01%) due to increase of the working hours of the generators;

- In EnergyPLAN, the model chose to supply the flexible demand during off-peak hours, even though there were no renewable energy sources, since the gap between nominal capacity of working generators and demand is higher during off-peak hours. However, due to the higher demand on group of generators #1 & #2, and decrease in the working hours and power committed for generators #3 & #4, there is a 0.08% decrease in the costs and diesel consumed.

Looking at ED model there is 0.3% savings in the operation costs and diesel consumption when compared to Scenario 2. The system has the same number of start-ups and shut-downs but the generators are working in regimes closer to the optimum, which induces the small decrease verified.

Nevertheless, a careful interpretation of Table V.9 and Table V.10 shows that, although the savings from applying DR actions seem to be very small, also the flexible load available for doing DR represented only 1.8% of the total load (Table V.3), so comparatively, the ED model is the one tool with more saving potential when comparing DR actions.

Of course, the more the tool is adequate and represents the closest constraints to the real case study, the more suitable it will be to provide an accurate understanding of the system dynamics and absolute costs. For example, ED model respects the minimum output power of the generators and the system's reserve operation (which are responsible for 1% to 3% increase in the operational costs compared with if they were not considered), that neither HOMER nor EnergyPLAN take in account, leading eventually to unfeasible states if a real implementation would occur based on these two tools.

5.5 Suggestions for improving the modeling of demand response strategies

From the comparison of these three tools regarding the evaluation of demand response action, we may conclude that:

- Since HOMER requires that the inputs are the total load and its percentage of flexible load, there is no information regarding the hours in which the flexible load would normally be met, without demand response. This could enable the model to remove more consumption than is possible in reality from some hours of the day; HOMER could also get advantage of the information on the partial load efficiencies to dispatch the flexible load in hours of lower load, instead of leveling it along the day;

- In EnergyPLAN there is the possibility to define an average flexible load within the month/week/day, but it does not allow defining different potentials for demand response for different days/months/seasons. This introduces a significant limitation to the model when seasonal flexible demands are considered, such as the one modeled here (domestic hot water backup loads differ with solar radiation and therefore from month to month). Also the impossibility of modelling flexible demands with an hourly time frame is a limitation; since EnergyPLAN already places flexible load on the off-peak, it would get better results (costs and diesel savings) if an efficiency curve was used instead of an average efficiency.
- The ED model uses genetic algorithms, at an hourly time step, to reschedule the placement of demand response, on a day-ahead, to optimize daily dispatch. The model can be adapted for different daily flexible loads, but for long-term energy assessments it should be modified for running for consecutive days, taking into account the transitions and energy needs between several days/weeks.

Overall, the modeling of demand response should allow the possibility of considering different potentials for load shifting across different hours, days and months. Furthermore, the modeling tools that consider demand response should be able to optimize the load shifting based on whether it results in economic, environmental or technical benefits, thus enabling studies on the potential impacts of demand response for consumer habits and routines.

6 Conclusions

Demand response is widely seen as a possible enabler for high penetrations of renewable energy sources, particularly in the case of isolated systems. A concrete application of demand response strategies is being envisioned for Corvo Island, Portugal, using the electric backup of solar hot water systems to improve the use of the diesel generators that currently supply the electricity in the island. It is expected that this system will also support the integration of renewable energy sources in the future, like wind energy.

However, modeling approaches of demand response strategies are still in early stages. In this study, the capability of three modeling tools (HOMER, EnergyPLAN and a self-built ED Model) to assess the potential for demand response in Corvo Island was studied. To compare the three modeling tools, three scenarios were designed: Scenario 1 considered a base load and no flexible demand, Scenario 2 considered a base load plus a fixed load but no flexible demand, and Scenario 3 considered a base load plus flexible demand.

Scenario 1 enabled the comparison of the three modeling tools with the actual operation. It was found that the self-built ED model presented results closer to the actual operation, as it includes several restrictions that exist on real operation conditions. HOMER and EnergyPLAN had lower costs and less diesel consumption.

It was found that HOMER and EnergyPLAN have different ways of dealing with demand response, which nonetheless did not impact significantly on the system estimated operation costs. While HOMER distributed the demand evenly throughout the day, EnergyPLAN shifted it to the off-peak hours, with little savings of 0.01% and 0.08% on operation costs and diesel consumption. The ED model observed the largest savings with DR, although being only 0.3% on operation costs and diesel consumption - obtained by rescheduling the DHW backup load with the aid of genetic algorithms optimization.

As such, HOMER and EnergyPLAN, two of the most used modeling tools for optimizing renewable integration, can still improve their modeling strategies for demand response analysis purposes. In order to model demand response strategies, these modeling tools should be able to optimize the demand shifting only if there is economic, environmental or technical benefits, or in alternative, they should include as input data the hourly potential to allocate flexible loads.

This study uses a day-ahead planning when performing demand response, but it also can be used as direct load control, which can help to ease some operation and dispatch constraints, being even more relevant in the presence of renewable resources. However, the study of direct load control should be performed using grid operation models, instead of EnergyPLAN and HOMER tools. The possibility to take DR actions will depend greatly on the flexibility of the tool to reproduce the real constraints and system's dynamics, and this requires the possibility to input more data and using the adequate time scale. Looking at the specific case study of Corvo, a possible DR implementation would be with the installation of controllers in the individual hot water tanks, together with a power and dispatch management algorithm on the grid operator side, which would enable a synchronized and centralized remote control, of the DHW backup.

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Chapter VI
Impact of solar and wind forecast uncertainties on demand response of isolated microgrids

Abstract

A flexible load management may improve significantly the economic dispatch, especially for isolated energy systems with a significant share of renewables. For that purpose, renewable resources and load forecasts ought to be taken in account for optimal demand response programs.

The present study uses solar forecast coupled with domestic hot water needs to anticipate the electric demand of solar thermal systems. On the other hand, wind electricity supply will take advantage of thermal storage of solar systems, using a demand response strategy based on genetic algorithms, for load optimization, in order to minimize overall operating costs. The methodology is applied to the isolated microgrid of Corvo Island, in Azores.

Results show a 3% increase in the dispatch costs due to the forecasts uncertainty, when in presence of 8% of daily flexible loads. However, this impact is dissipated when solar thermal backup needs decrease, which is explained by the relevance of the wind forecast on the planning of the dispatch of flexible loads. Wind forecast uncertainties can impact in 2% in absorption of wind energy, varying with the forecast horizon considered, while the solar forecast uncertainties have more impact when the thermal energy storage is below the daily thermal demand.

Keywords

Demand response; Forecast uncertainties; Microgrids; Thermal storage; Hybrid renewable energy systems; Economic dispatch

1 Introduction

Demand Response (DR) is expected to increase flexibility and easier integration of renewable energy in the electric power systems since it can help matching the load with the renewable's resources but also because it serves as load curtailment in order to assure security of supply [1] and postpone additional investments [2]. This is particularly relevant for isolated systems, as these systems cannot export the excess of renewable energy to another region, as interconnected systems can, thus making renewable forecast critical for the management of the energy system.

An isolated system should have preferably more than one energy source for reliability and security of supply, and hybrid renewable energy systems are therefore particularly suited for smaller systems: diesel, wind and solar are the top energy sources chosen, although the choice often relies on which was the previous energy system and which renewable resources are mostly available at the location [3]. While renewable energy normally requires high investment costs, its operation costs are almost negligible when compared to diesel. Nevertheless, diesel takes an important role assuring the necessary system regulation and control.

Renewable resources variability and its influence on energy systems, along with demand response, has already been the core of some studies: both [4] and [5] use Flores Island, in Azores, to study respectively, the impact of modeling renewables' integration with different planning horizons, and the influence of demand response in the renewable penetration in the long-term; in [6] the integration of renewable energy on a microgrid is economically compared with demand response; in [7] a multi-agent system is developed to manage thermal storage as demand response with increasing renewables' penetration.

Forecast uncertainties are not yet completely included in the management of energy systems but may have great impact on isolated microgrids, as it can lead to load following and dispatch problems [8]. Their impact on the integration of renewables in the energy system dispatch has been little explored, but there are some examples in the literature: in [8], a probabilistic software tool that integrates wind, load and generation forecast uncertainties into dispatch requirements is developed for California state; in [9] a model of predictive control is used to keep solar and wind forecast uncertainties at acceptable levels, by compensating with storage capacity (thermal and batteries); in [10], the wind power uncertainty is taken into account on the wholesale electricity market, showing increase in the net earnings for wind sales; and in [11] a model that takes into account the thermal, water, wind, solar and load uncertainties on a fuzzy optimization of the generation schedule, regarding the hydro and thermal power plant generation, is presented. In particular, there is no work found on analyzing the impact of the renewables uncertainties on demand response strategies.

This paper proposes to analyze the influence of using renewables' forecast and its uncertainties on the optimization of demand response of the economic dispatch of an isolated microgrid system. The hot water tanks of the solar thermal systems will act as storage, and its electrical backup is the flexible load to be managed through demand response. The inclusion of the solar forecast to determine the real hourly needs will be used to test if more wind powered electricity can be absorbed. Further, a sensitivity analysis is performed to determine which renewable forecast best benefits the energy system. This methodology is applied to Corvo Island, in Azores, a small and isolated community in the mid-Atlantic Ocean. Corvo Island is currently 100% dependent on diesel for electricity supply, but the implementation of wind turbines is being studied. Also solar thermal systems and heat pumps for domestic hot water (DHW) supply were recently installed in the island, which represent the thermal storage capacity.

The paper is organized as follows. Section 2 presents renewable forecast methods and those used for solar and wind in this paper; Section 3 describes the Corvo Island case study; in Section 4, the methodology for implementation to the case study is described, while in Section 5 the results are presented together with a sensitivity analysis. Section 6 makes the final statements of the work.

2 Forecast of renewable resources

The integration of the uncertainty of renewable generation on energy systems introduces additional challenges to the dispatch of power systems, both in terms of operation and costs [12]. An accurate forecast reduces the balancing needs and required reserve power, in general assured by fast-diesel backup or storage devices, with higher costs.

Due to its simplicity and ubiquity, the persistence model is usually taken as the benchmark for forecasting and it is therefore used in this study (Section 2.1) to assess the impact of forecast uncertainties. Short-term forecasting models were chosen, since the aim is to optimize the dispatch on a day-ahead/week ahead planning. A time-step of 60 minutes (t=1 hour) was considered for both solar and wind forecasts, since power related systems are operated with that interval (among others more refined, such as 5 or 15 minutes) [13]. It ought to be mentioned that the persistent type forecast is more suitable for locations where the weather regimes are more stable, rather than for places with abrupt weather changes. However, this work focus more on introducing the uncertainties of renewables forecast than on the forecast model used, in order to model a more realistic scenario.

2.1 Solar forecast

Although solar energy can be considered more predictable than other renewable resources (wind, waves, etc.), as it is a consequence of the cyclic movement of the Earth, at the ground level it depends highly on the atmosphere and consequent cloud cover, which may have a large impact on the local grid operation [14].

There are many solar forecasting methods, suitable for different time scales that are comprehensively reviewed in [15]. For this particular analysis, where the solar forecast is used to assess the solar thermal production of hot water and consequent electric backup needs, the basic hourly clear sky persistence model was considered, which is usually taken as the benchmark against which all proposed methods are compared.

The persistence model is defined by [16] as a simple forecasting model that only requires knowledge of clear sky irradiance, i.e. the solar irradiation that one would have without clouds. Usually, this simple forecasting tool is very accurate for short-time horizons and for low irradiance variability. The model considers that the clear sky index persists for the next time-step, thus following Equations VI.1 and VI.2:

$$k(t+\Delta t) = k(t) = \frac{I_{measured}(t)}{I_{clr}(t)} \quad \text{(VI.1)}$$

$$I_{forecast}(t+\Delta t) = k(t)\, I_{clr}(t+\Delta t) \quad \text{(VI.2)}$$

where $k(t)$ is the clear-sky index at a certain instant t, $I_{measured}(t)$ is the global horizontal solar irradiance, and $I_{clr}(t)$ is the global horizontal irradiance for clear sky conditions, both for that same instant t, calculated according to [17], albeit other models have been proposed [18].

Based on the available data [18] for this particular implementation, the clearness index was used instead of the clear-sky index, as it only differs in the normalization factor used in its definition [15], referring to extraterrestrial irradiation instead of clear sky, which were substituted accordingly in the above equations.

2.2 Wind forecast

Due to the complex nature of wind and growing integration of wind energy on the energy systems, there is an increasing need to evaluate the uncertainty on the wind forecast.

In general, wind forecast is described in terms of physical methods [19], statistical methods [20] or learning methods, as artificial neural networks [21][22]. There are also hybrid approaches [23], which mix some of these methods to achieve better results both in the long and short-term prediction. In [24][25] the authors present an extensive review on wind forecasting and prediction models, regarding also their adequacy for different geographical and time scales. In order to test their suitability, the associated errors are normally calculated and compared with the classic persistence model.

Similarly to what was considered in the solar forecast, the forecasting model considered for the wind speed is an hourly persistence model, where the wind speed forecast for a certain hour is equal to the wind speed measured on the hour before. This model is a frequent approach for dispatch purposes [26], since it is considered as robust and reliable for short-term forecasting [10]. Equation VI.3 presents this relation, where $u_{forecast}$ is the forecasted wind speed, and $u_{real}(t)$ is the real wind speed measured at instant t.

$$u_{forecast}(t + \Delta t) = u_{real}(t) \tag{VI.3}$$

2.3 Forecast errors

The forecast errors are used to evaluate the capacity of the implemented forecasting methods to fit the on-site/real measures.

The common error indices used in the renewables' forecasting methods are presented in Equations VI.4, VI.5, VI.6 and VI.7, and correspond respectively to the Mean Absolute Error (MAE), the Mean Absolute Percentage Error (MAPE), the Root Mean Square Error (RMSE) and the Mean Bias Error (MBE) [15]:

$$MAE = \frac{1}{N}\sum_{t=1}^{N}|P_t - M_t| \tag{VI.4}$$

$$MAPE = \frac{100\%}{N}\sum_{t=1}^{N}\left|\frac{P_t - M_t}{M_t}\right| \tag{VI.5}$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{t=1}^{N}(P_t - M_t)^2} \tag{VI.6}$$

$$MBE = \frac{1}{N}\sum_{t=1}^{N}(P_t - M_t) \qquad \text{(VI.7)}$$

where N is the total number of measured values, P_t is the forecast value, and M_t the measured value for a certain renewable resource.

The RMSE and MAE are the most interesting to observe, since they provide complementary information: MAE measures the average magnitude of the errors in a set of forecasts, without considering their sign, while RMSE reports the degree of dispersion of the two variables (forecast and real data) correlated around a mean expected value. RMSE will always be equal or larger than MAE since it reports the variance of the individual errors, while if RMSE and MAE are equal, than all the errors have the same magnitude.

3 The Corvo Island case study

Corvo is the most remote and isolated island of the Azorean Archipelago, located in the middle of the Atlantic Ocean. Corvo has 430 inhabitants, living in 144 houses [27], and is externally dependent for goods and energy. The main economic activities are livestock, fishing and agriculture.

3.1 Energy system

Corvo's energy system is composed by a diesel power plant with 4 generators, with a total capacity of 536 kW. Further details and operation constraints are described in Table VI.1. Ramp up and down rates are considered to be instantaneous and no start-up/shut down periods were considered.

At the end of 2014, the Regional Government and the local utility *Electricidade dos Açores* (EDA) installed 66 solar thermal systems (ST) and 78 air-water heat pumps (HP), in order to supply the domestic hot water that, until then, had been supplied by liquefied petroleum gas (LPG). The high transportation costs and the frequent unavailability of LPG in winter due to bad weather, has led to this decision [28]. Moreover, other studies on implementing renewable technologies for electricity generation are being done, as the installation of wind turbines.

Table VI.1 - Diesel Generators characteristics and constraints

Generator	**Nominal Power** [kW]	**Minimum output** [kW]	**Fuel Consumption** [l/h]			**Minimum up/down time** [h]	**Start-up cost (cold/hot)** [€]
			100% Pnom	75% Pnom	50% Pnom		
#1 #2	108	42	31.2	24.2	17.4	4/2	20/0
#3 #4	160	64	49.4	37.4	25.6	5/3	30/0

3.1.1 Electricity demand

In the absence of a services' sector, the residential sector is the largest consumer of electricity in the island.

The electrification of DHW systems introduced additional stress to the existing grid, increasing the annual electric load in 7%. A large share of the increase can be assigned to the HP, and the power peak increase of 50% is mainly due to the ST systems in days of low radiation [28]. Table VI.2 summarizes the electricity and peak demand after the installation of the DHW systems, together with the associated electric backup needs.

Table VI.2 - Electric loads in Corvo Island after the installation of the DHW systems

Electricity Demand		**Peak**		**DHW backup needs**	
Annual load [MWh/yr]	Average Daily Load [MWh/day]	Annual Peak [kW]	Average Daily peak [kW]	HP [MWh/year]	ST [MWh/year]
1471	4.03	359.85	255.02	67.52 (4.6%)	24.79 (1.7%)

As Corvo is an isolated microgrid, this load increase had a significant impact on the diesel power plant. However, it is very difficult to implement end-user incentives based on price signals apart from the regulated dual tariff, in such small system operating under regulated market. Thus, demand response from the grid operation point of view seems to be an interesting approach to manage the additional loads introduced by DHW systems in the island.

3.2 Solar data

The solar data for Corvo used in this study is a 22-year average provided by NASA database [29]. The daily solar horizontal irradiation for Corvo Island is presented in Figure VI.1, while Figure VI.2 and Figure VI.3 present a comparison between the forecast model and the real data for a winter and summer week, respectively.

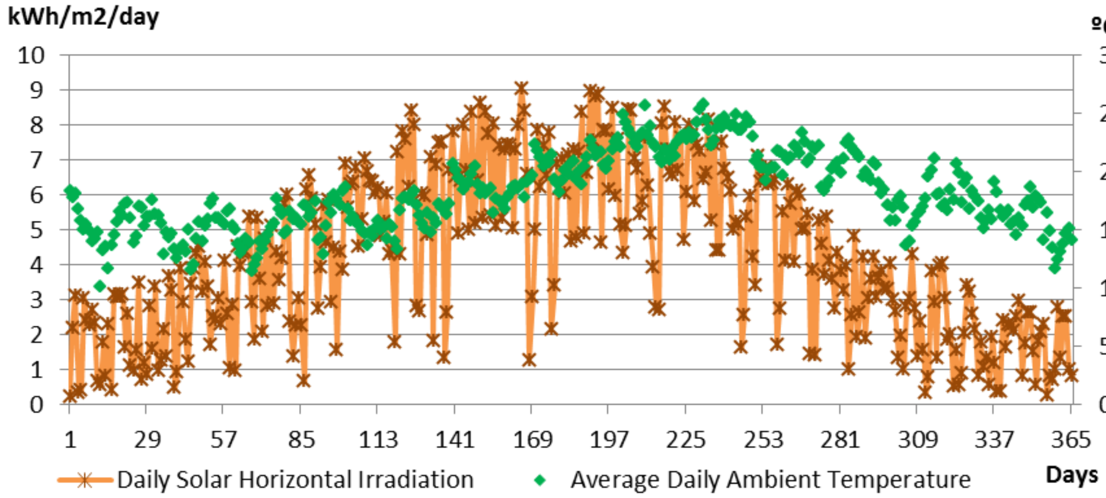

Figure VI.1 - Daily solar horizontal irradiation and average daily ambient temperature for Corvo Island [29]

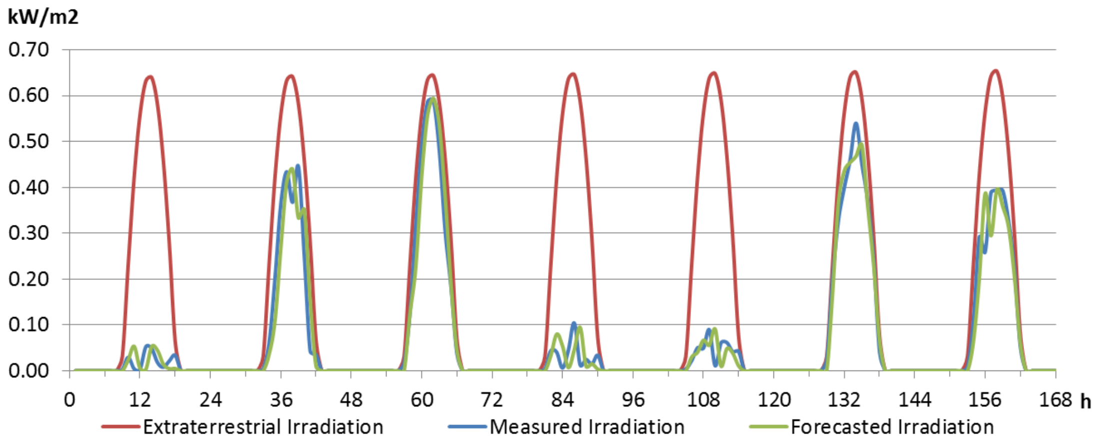

Figure VI.2 - Comparison between forecast and measurements for a winter week

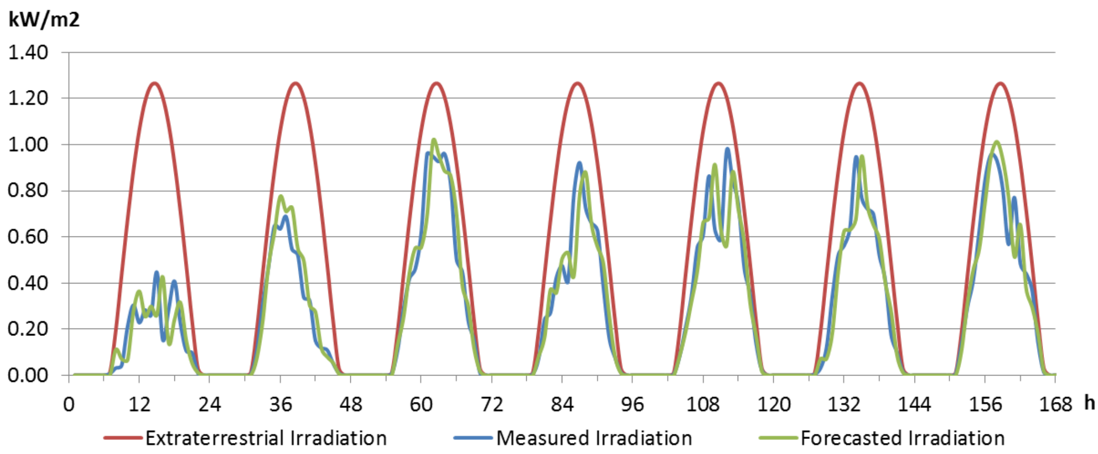

Figure VI.3 - Comparison between forecast and measurements for a summer week

Table VI.3 - Solar forecast errors of Corvo, compared to real data

Season	**MAE** [kW/m^2]	**MAPE** [%]	**RMSE** [kW/m^2]	**MBE** [kW/m^2]
Annual	0.033	19.034	0.065	-1.63e-05
Winter	0.019	20.423	0.041	-1.10e-03
Spring	0.039	20.306	0.075	1.10e-03
Summer	0.044	17.679	0.081	8.91e-04
Autumn	0.027	17.742	0.055	-9.94e-04

3.3 Wind data

The wind speed data was provided by the local utility, EDA [30], and measured *in situ* at *Morro da Fonte,* where the implementation of wind turbines is being studied. Figure VI.4 and Figure VI.5 present, respectively, the daily average wind speed, and the wind speed distribution per % of frequency, measured at 25 m of height.

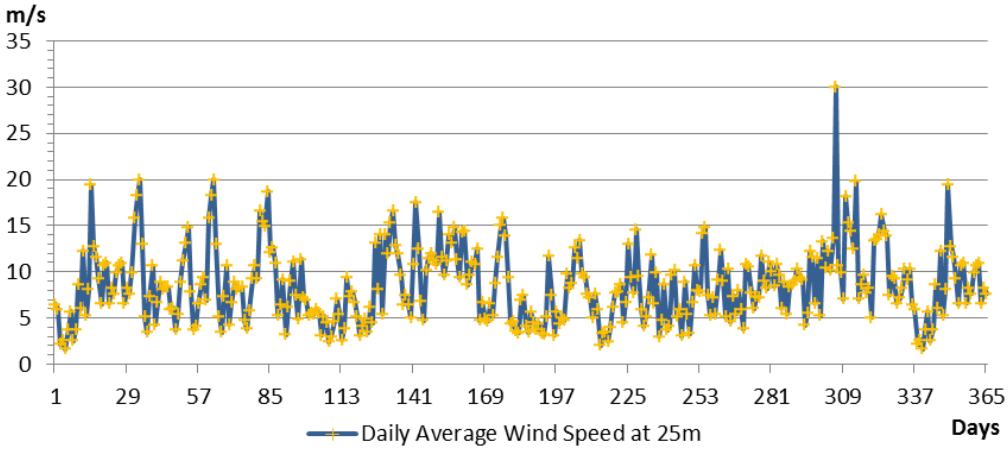

Figure VI.4 - Daily average wind speed at 25m

Table VI.4 presents the annual and seasonal wind power forecast errors. It is interesting to observe that the MAE is considerable higher than for solar, which can be explained by the higher hourly variability of wind speed, with its maximum in autumn, achieving an annual 72% error in terms of percentage (MAPE). Looking at RMSE, it is annually observed a dispersion of 34 kW (around 12% the nominal power of 275 kW). Given these errors, although the wind power forecast model can be improved, for the work here considered it presents sufficient precision.

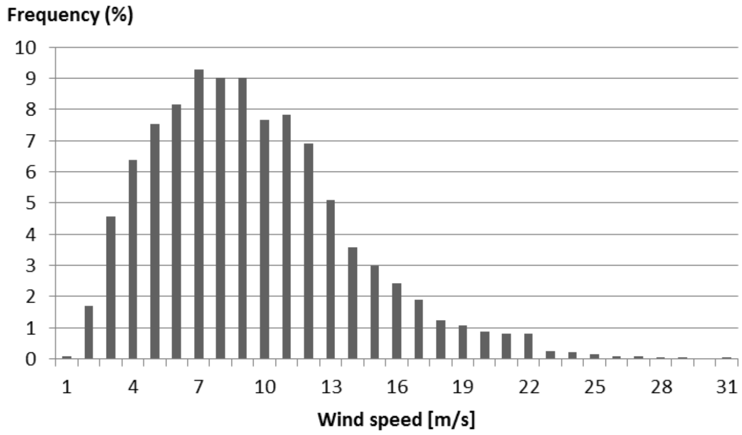

Figure VI.5 - Corvo's wind speed distribution

Table VI.4 - Wind power forecast errors compared with real data

Season	**MAE** [kW]	**MAPE** [%]	**RMSE** [kW]	**MBE** [kW]
Annual	18.308	72.780	33.751	-2.43e-17
Winter	17.555	66.874	30.577	1.48e-2
Spring	17.250	58.872	32.700	-9.68e-2
Summer	14.973	70.338	27.154	1.01e-1
Autumn	23.492	95.152	42.636	-1.91e-2

The turbine proposed in the study has a rated power of 275 kW and the power curve presented in Figure VI.6.

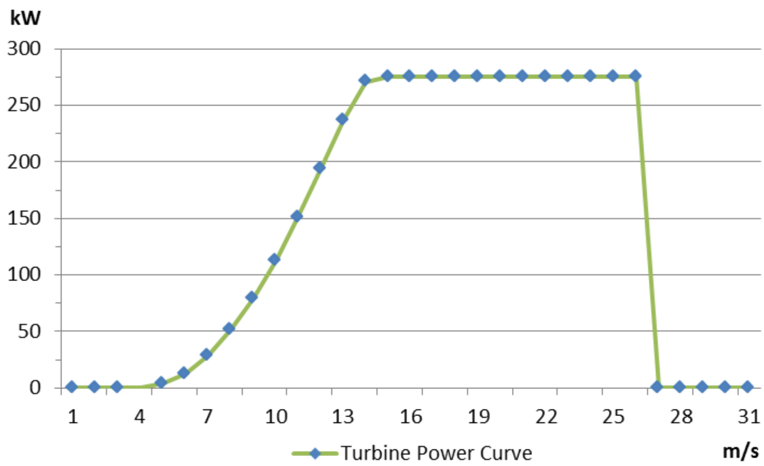

Figure VI.6 - Wind turbine power curve

4 Implementing renewables' forecast on optimal dispatch

4.1 Solar resource daily forecast

The hourly analysis of the solar resource is crucial to introduce the constraints in the thermal storage model since a global daily balance of thermal needs and solar gains would not take into account the real backup needs. Take as an example a day where the balance between total daily solar gains and daily thermal demand is positive; at the, hourly level, when the thermal demand occurs very early in the morning, there may be a lack of hot water available in the storage tank. In the first approach, there is no need for electric backup, while the second approach requires electric backup early in the morning. This mismatch between solar gains dynamics and thermal demand, leads to the need to introduce a short term horizon, with at least an hourly resolution.

To observe this effect on the dispatch model, the DHW electric impact model developed in [28] was adapted to provide the solar gains per ST system and the thermal needs of the consumers, as described by Equation VI.8 and VI.9, respectively:

$$Q_{solar}(\mathrm{t}) = \frac{A_{abs}}{1000}.(\mathrm{I_{col}}(t).\eta_{col}\text{-}(\frac{\mathrm{U_c}.(\mathrm{T_m}(t)\text{-}\mathrm{T_{amb}}(\mathrm{t}))+\varepsilon.\sigma.(\mathrm{T_m}(t)^4\text{-}\mathrm{T_{inlet}}(t)^4)}{8760});\quad Q_{solar}(\mathrm{t})\geq 0\ \ [\mathrm{kW}] \qquad \text{(VI.8)}$$

where:

- A_{abs} is the area of the flat-plate collector,
- $\mathrm{I_{col}}(t)$ is the hourly solar irradiation on the collector plane [W/m²],
- η_{col} is the collector efficiency,
- $\mathrm{U_c}$ is the conductive loss' coefficient,
- ε is the emittance,
- σ is the Stefan-Boltzmann constant,
- $\mathrm{T_{amb}}(t)$ is the hourly ambient temperature,
- $\mathrm{T_{inlet}}(t)$ is the hourly inlet water temperature on collector and,
- $\mathrm{T_m}(t)$ is the hourly average temperature defined by $\mathrm{T_m}(t) = \frac{\mathrm{T}_{max}+\mathrm{T_{inlet}}(t)}{2}\ [K]$

$$\mathrm{Q}_{DHW}(t) = \frac{C_{p\ water}.\rho_{water}.V_{DHW}(t).(\mathrm{T_{max}}-\mathrm{T_{inlet}})}{1000.3600}\ [kW] \qquad \text{(VI.9)}$$

where:

- $C_{p\ water}$ is the specific water heat (4.186 KJ/kg.K);
- ρ_{water} is the water density (1000 kg/m³);
- V_{DHW} is the volume, in liters, of hot water demand at each hour t.

Three equally distributed groups of consumers are considered: the *Morning* consumers (mainly morning demand), the *Evening* consumers (mainly evening demand) and the *Distributed* consumers (where the thermal demand is distributed throughout morning, midday and evening) [28]. In a first stage of forecast, the inputs (forecasted solar gains, $Q_{solar\_forecast}$) and outputs (hot water demand Q_{DHW}) of the tanks were cumulatively summed, at each hour, for each demand profile, as represented in Equation VI.10:

$$\begin{cases} \Delta Tank(t) = cumsum\big(Q_{solar}(t) - Q_{DHW}(t) + tank(t-1)\big) \times nr.houses\_profile \\ \quad 0 \leq \Delta Tank(t) \leq Qtank_{max} \times nr.houses_{profile} \end{cases} \tag{VI.10}$$

where $Qtank_{max}$ is the maximum storage capacity of the each system, and $nr.houses\_profile$ is the number of houses per consumption profile.

On a second stage, Equation VI.10 is evaluated for each DHW profile, to determine the three maximum daily backup needs and the respective hours at which they occur, using Equation VI.11:

$$\begin{cases} Max_{need} = \|\min(\Delta Tank, 0)\| \\ \quad t_{max} \rightarrow \min\big(\Delta Tank(t)\big) \\ \quad\quad t_{max} = t_{max} - 1 \end{cases} \tag{VI.11}$$

With this formulation, the third stage consists of finding out the islands' total daily backup needs, summing the backup needs of each profile (Equation VI.12), according to the solar forecast and hot water demand, assuming that the backup is constrained by the energy stored in the tanks and their capacity.

$$Max_{backup} = \sum_{i=Morning,Evening,Distributed}^{3} Max_{need} \tag{VI.12}$$

4.2 Wind power forecast

The wind power forecast is introduced in the algorithm as another power generator, where the nominal power at each hour corresponds to the wind power available, given the wind speed forecast and the turbine power curve (previously presented in Section 3.3). However, due to operational constraints [31], it is considered that the wind park cannot operate alone, which means that there is always at least one diesel generator working, to assure the existence of a spinning reserve for power quality and regulation purposes.

If the electric load is lower than the sum of the committed capacity of the generators, the wind turbine will work below its maximum capacity, which implies that it will decrease the life expectancy of the wind turbine. In this context, flexible load to manage along the day can be an opportunity to increase wind penetration of in the system and improve its management [32].

4.3 Genetic algorithms to optimize the placement of DHW backup needs

In this paper, it is assumed that the DHW backup is centrally managed by the utility through a demand response program, in order to minimize the operation costs of the system. The ultimate goal is to maximize the penetration of renewables (solar and wind) and consequently minimize the diesel consumption of the power plant for electricity production and/or spinning reserve. The backup schedule is generated by the implementation of a Genetic Algorithms (GA) optimization approach, adapted from the formulation introduced in [33] and improved to harness more wind energy to cover the ST backup loads.

Genetic algorithms optimization was chosen against other linear options, since it has been demonstrated [33][34] to be suitable and flexible for this problem formulation, presenting the best performance to minimize the operations costs and peak demand, with few dispersion among results, even being a non-linear optimization method.

4.3.1 Initializing and validation

First, a random population of DHW energy needs is initialized: a matrix of dimension *[n x m]* where n is the population size and m is the number of genes, i.e., the number of time periods under analysis. Each gene x_{nm} (matrix entry) represents the amount of backup power [kW] at each time period – in this case hour – as described in Equation VI.13:

$$population = \begin{bmatrix} x_{11} & \cdots & x_{1m} \\ \vdots & \ddots & \vdots \\ x_{n1} & \cdots & x_{nm} \end{bmatrix} \tag{VI.13}$$

Each row of the population is a *chromosome*, being each element x_i within it, subject to certain restrictions, as observed in Equation VI.14: if the sum of the forecasted wind power is higher than the daily DHW backup needs, then the backup power x_i, in each moment, will be a percentage of the nominal power ($Pnom$) of each ST system, regarding the totality of the islands' systems. The backup power x_i for a certain instant t has as upper limit the forecasted wind power available for that hour - this restriction will foster the absorption of wind energy through demand response; and if the totality of the daily wind power available is less than the DHW backup needs, then the backup power x_i is just defined as random a percentage of the nominal power of the totality of the systems.

$$given\ \ chromosome = [x_1 \quad \dots\ x_i \dots \quad x_m]$$

$$\begin{cases} if\ \sum wind\ power_{forecast}\,(1{:}\,m) >\ Max_{backup} \\ x_i = \%\ Pnom \times nr.houses_{total}\ ; 0 \le x_i \le wind\ power_{forecast}(i) \\ else \\ x_i = \%\ Pnom \times nr.houses_{total} \end{cases} \tag{VI.14}$$

Before the fitness is evaluated using the economic dispatch function, the chromosomes are verified to check if the backup is done before the hour d - the latest hour at which DHW is required between the three t_{max} of each profile - as seen in Equation VI.15: if they are lacking, random values proportional to the difference between needs and backup, are added; if the backup loads are exceeding, a proportion of that difference between needs and backup is subtracted to the solution, and distributed along d hours.

$$\begin{cases} if \sum_{i=1}^{d}\ x_i < Max_{backup} \\ chromosome\ (1{:}\,d) = chromosome\ (1{:}\,d) + random(1{:}\,d) \times \Delta b \\ else \\ chromosome\ (1{:}\,d) = chromosome\ (1{:}\,d) - \frac{-\Delta b}{d} \end{cases} \tag{VI.15}$$

with $\Delta b = \ Max_{backup} - \sum_{i=1}^{d} \ x_i$, where Max_{backup} was defined in Equation VI.12.

In this work, a strategy of changing all the genes to zero once the cumulative sum of the chromosome meets the double value of the maximum backup, is followed. This, by one hand, acts as a filter to the solutions that promote excessive backup, and on the other hand, broadens the probability to find solutions near the optimal ones.

4.3.2 Cost function and penalties

The cost function consists of minimizing the economic dispatch function combined with the unit commitment problem, taking into account various operational constrains of the generating technologies, such as start-up and shut-down costs, minimum up and down time, ramp up/down rate, minimum power output and operating reserve, as introduced in [33]. The sum of the DHW needs of each chromosome is summed to the island hourly load, and tested on the dispatch model. The dispatch function optimizes the commitment of the available generators, at each hour, for a given demand, checking for the feasibility of the transitions of each state of commitment, accounting with the operational constraints presented in Table VI.1. The model works with an hourly time-step, and provides the generators committed at each hour, and the total dispatch and generations costs, which the main difference is that the first accounts with start-up and shut-down costs and the second only with the diesel costs.

To guarantee that the DHW needs are satisfied, after running the economic dispatch model, a penalty is introduced to the dispatch costs, in case the overall backup needs are not met or are exceeded. Different weights in the penalties are given to the solution according to its fulfillment with the backup needs, and the summary of the applied penalties are presented by Equation VI.16, VI.17 and VI.18:

- If it meets the overall backup needs, the penalties are lower even if it does not meet the hour it should (Equation VI.16);
- If it does not meet the overall backup needs, the penalties are higher (Equation VI.17), since it causes a problem of satisfaction to the end-user;
- If it exceeds the backup needs, the penalties are lower than if it does not meet (Equation VI.18). Although it brings excess of electricity that cannot be absorbed by the grid, that is a small problem to the grid manager but not to the end-user, that has his thermal needs satisfied.

$$if \sum_{i=1}^{m} \ x_i = Max_{backup} \wedge \begin{cases} \sum_{i=1}^{d} \ x_i = Max_{backup} \ \rightarrow penalty = 0 \\ \sum_{i=1}^{d} \ x_i < Max_{backup} \ \rightarrow penalty = p \\ \sum_{i=1}^{d} \ x_i \geq Max_{backup} \ \rightarrow penalty = \frac{1}{2}p \end{cases} \tag{VI.16}$$

$$if \sum_{i=1}^{m} \ x_i < Max_{backup} \wedge \begin{cases} \sum_{i=1}^{d} \ x_i = Max_{backup} \ \rightarrow penalty = \frac{1}{2}p^2 \\ \sum_{i=1}^{d} \ x_i < Max_{backup} \ \rightarrow penalty = 2\,p^2 \\ \sum_{i=1}^{d} \ x_i \geq Max_{backup} \ \rightarrow penalty = p^2 \end{cases} \tag{VI.17}$$

$$if \sum_{i=1}^{m} x_i \geq Max_{backup} \wedge \begin{cases} \sum_{i=1}^{d} x_i = Max_{backup} \rightarrow penalty = \frac{1}{4}p^2 \\ \sum_{i=1}^{d} x_i < Max_{backup} \rightarrow penalty = p^2 \\ \sum_{i=1}^{d} x_i \geq Max_{backup} \rightarrow penalty = \frac{1}{2}p^2 \end{cases} \quad \text{(VI.18)}$$

where p is a penalty factor defined by $p = 2\|\Delta b\|$.

The penalties described are to be applied to the output of the cost function.

4.3.3 Selection, Cross-over and Mutation

The particularity of genetic algorithms is that they undertake natural processes such as selection, cross-over and mutation.

In this work, to select the fittest chromosome to qualify for the next generation, the selection process used was the tournament wheel, since it is widely used for minimization problems. A tournament size of 2 was used, and so randomly two chromosomes were chosen and then filtered the best individual out of that set to enter as a new chromosome in the next generation.

After, the cross-over was applied. The cross-over is a crucial operator, since it will cross the information of two (or more) chromosomes to origin a new chromosome [35]. The method used was the single point cross-over, with a probability of cross-over of 70%.

Mutation was also applied in this context, using uniform mutation with a probability of 5%. Although mutation is an occasional process, it consists of a random exchanging of genes on a certain element [35].

4.4 Algorithm implementation

Figure VI.7 presents a flowchart of the implemented algorithm to test the effectiveness of integrating the solar and wind forecast information in the demand response strategy, in order to optimize the economic dispatch of the isolated microgrid of Corvo Island. In the flowchart, the parallelograms (orange) indicate the inputs, the rectangles (white) describe the processes and the squares (green) the outputs.

Regarding the forecasts, some indices were defined:

- *forecast horizon* (FH) – corresponds to the period for which the forecast is being determined and to which the dispatch is also evaluated: 24h were used as base, and were tested also 72h (3 days) and 168h (1 week);
- *forecast frequency* (FF) – defines the time-step at which the dispatch planning is updated with real inputs (solar data, wind data, load evolution, etc.): 3h, 6h and 12h were tested;
- *dispatch horizon* (DH) – determines the effective horizon of the dispatch planning each time a forecast update is done: a day-ahead basis was used (i.e. 24h), but were also tested 48h and 72h.

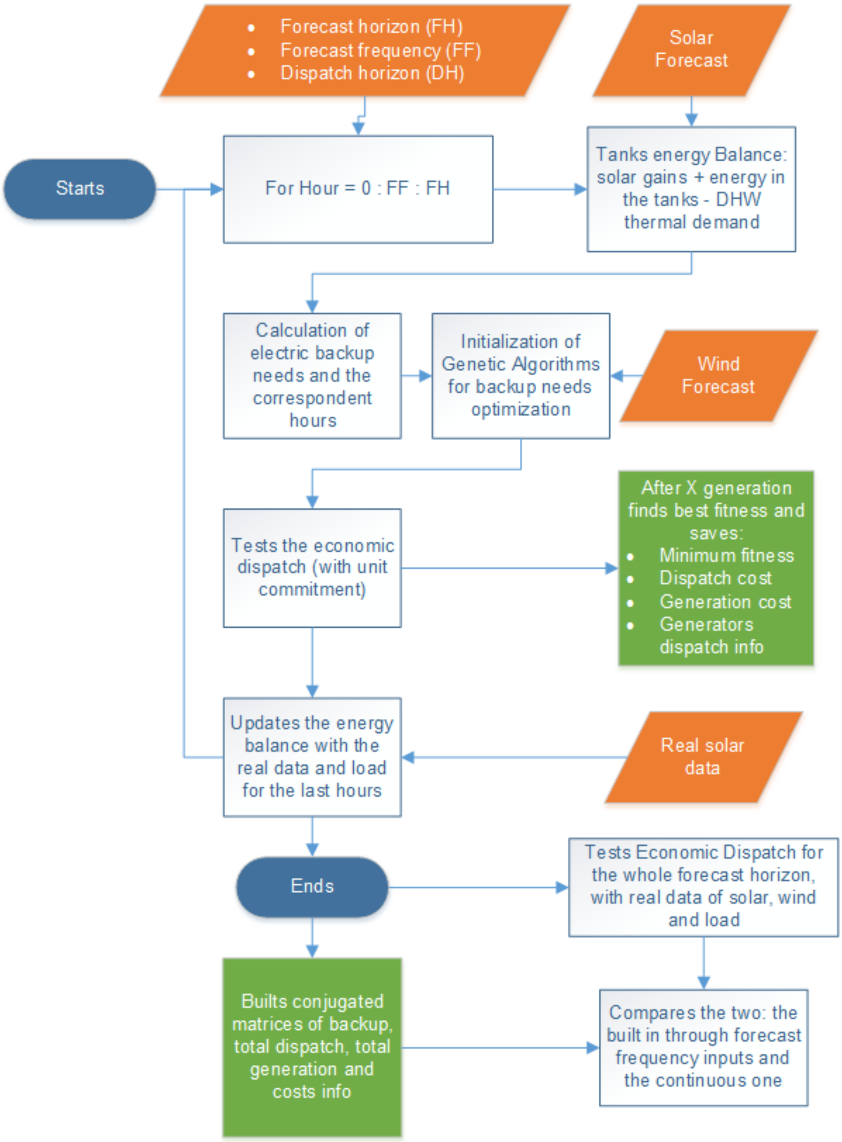

Figure VI.7 - Flowchart of the algorithm implemented

5 Results

A sensitivity analysis was made to the forecast horizon and frequency. The simulations done with the different indexes' combination are described in Table VI.5. For each problem instance, the algorithm ran 3 times, and the maximum dispersion between results for each simulation is also presented in Table VI.6, Table VI.8 and Table VI.10.

Table VI.5 - Simulations done with different combinations of indexes

Dispatch horizon [h]	**Forecast Horizon** [h]	**Forecast frequency** [h]	**Population size**	**Number of Generations**
24	24	3 / 6 / 12	10	20
	72			
	168	6		
48	168	12		
72				

In order to compare the influence of the uncertainty on the demand response, variables relating to cost were used, using energy related variables to compare the performance of the algorithm. The variables used are summarized next:

- *Minimum fitness* – corresponds to the total dispatch costs plus the penalty applied (as described in Section 4.3.2), for the forecasted model, for the forecast horizon considered;
- *Dispatch costs* – refers to the total dispatch costs for the forecast horizon;
- *Generation costs* – regards the total operation the costs with diesel consumption, for the forecast horizon;
- *Backup needs* - corresponds to sum of the daily Max_{backup} (previously introduced in Section 4.3.2) for the forecast horizon;
- *Backup done* – sum of the daily DHW backup loads allocated per forecast horizon;
- *Unattended needs* – difference between *Backup needs* and *Backup done*;
- *Zero-uncertainty dispatch costs* – are the dispatch costs calculated with the real resources availability, i.e. with Zero uncertainty, for the total forecast horizon;
- *Uncertainty impact on dispatch costs* – is the difference in the dispatch costs, between forecast and zero-uncertainty models, taking as reference the zero-uncertainty model.

In the results comparison, the best results appear in bold green and the worst in italic red. A maximum dispersion between results is presented in percentage of the dispatch costs.

5.1 Day-ahead planning and different wind regimes

Table VI.6 presents the results for the day-ahead planning (24 hours), for different forecast frequencies for a typical day with hourly wind variation, and comparing it with a wind stable day with no wind power variation, in order to observe the impact of different weather regimes.

Regarding the simulation for the day with stable wind speed, it is observed that, besides the solar forecast isn't stable, the uncertainty on the dispatch costs is null, and that is a direct consequence of the influence of the wind forecast on the determination on the dispatch (that in this case, as the wind power is constant, is the same for the real wind results), since they take full advantage of having a stable nominal wind power of 275 kW along the day (Figure VI.8). Also the fact that the solar forecast is used to determine the DHW electrified needs, takes advantage of the thermal inertia of the hot water tanks, determining that the solar forecast will be more useful for assuring security of hot water supply with more energy efficiency. This dynamic approach presents savings that can achieve 4% in winter, on an only diesel powered energy system, when compared to an approach using seasonal averages [36]. However, when in presence of large penetration of wind energy the solar forecast uncertainties are not significant on a day-ahead horizon, but they might be for longer horizons as seen further.

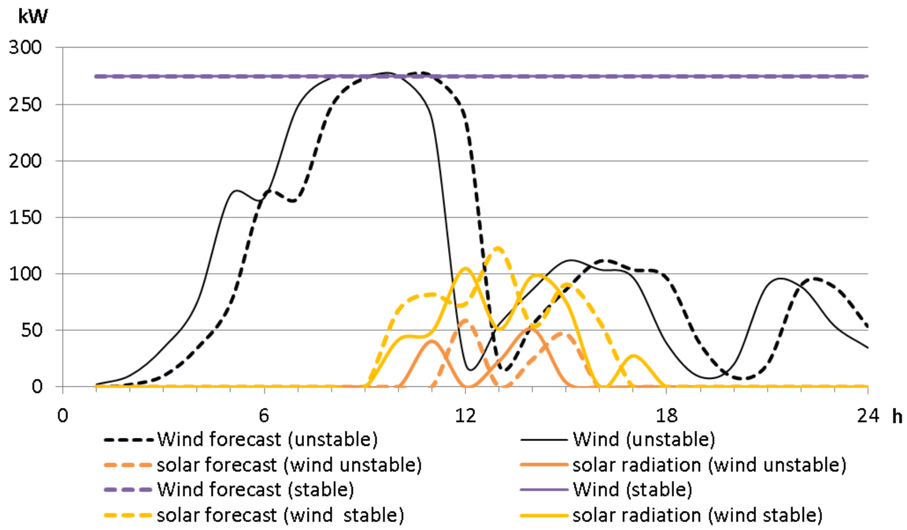

Figure VI.8 - Comparison of different wind regimes

Table VI.6 - Comparison results for DH/FF/FF = 24/24/3-6-12 and different wind regimes

Wind hourly variation		unstable		stable
Population Size/Generations		10/20		10/20
Dispatch horizon [h]		24		24
Forecast horizon [h]		24		24
Forecast frequency [h]	3	6	12	6
Maximum dispersion [%]	+4.5%	+1.3%	+1.6%	0%
Minimum fitness [€]	*721.44*	551.76	603.04	248.12
Dispatch costs [€]	*528.87*	525.13	528.72	238.04
Generation costs [€]	*478.87*	475.13	478.72	238.04
Backup needs [kWh/day]	274.67	274.67	274.67	67.38
Backup done [kWh/day]	306.49	211.79	149.28	116.38
Unattended needs [kWh/day]	-31.83	62.87	*125.39*	0
Zero-uncertainty dispatch costs [€]	*517.05*	511.62	515.21	238.04
Uncertainty impact on dispatch cost [€]	+2.3%	+2.6%	+2.6%	0%

For the different forecast frequencies (3h, 6h and 12h), Table VI.7 presents the wind absorbed by the same models, while Figure VI.9 presents the models' behavior regarding the wind penetration: the forecasted and real wind power available for the simulated day, and the power used by both forecasted (*FF_f*) and zero-uncertainty models (*FF_zu)*.

It is observed that although the forecasted and zero-uncertainty models have one hour difference, which is explained by the nature of the persistence model, the models place the ST loads at hours where they can be assured by wind energy. Moreover, the wind energy is used in full capacity by all the models, except in the period [4h-12h] when there is too much wind energy, leading to the placement of the flexible loads at these hours – during which there is only one diesel generator working on its minimum capacity. It is interesting to observe that the zero-uncertainty models lead to an increase of only 0.2%, on average, in the wind absorbed.

Table VI.7 - Wind absorption for DH/FH/FF=24/24/3-6-12

	Wind absorption [%]		
Model	FF=3	FF=6	FF=12
Forecast	46.03%	45.27%	43.86%
Zero-uncertainty	46.04%	45.52%	44.12%

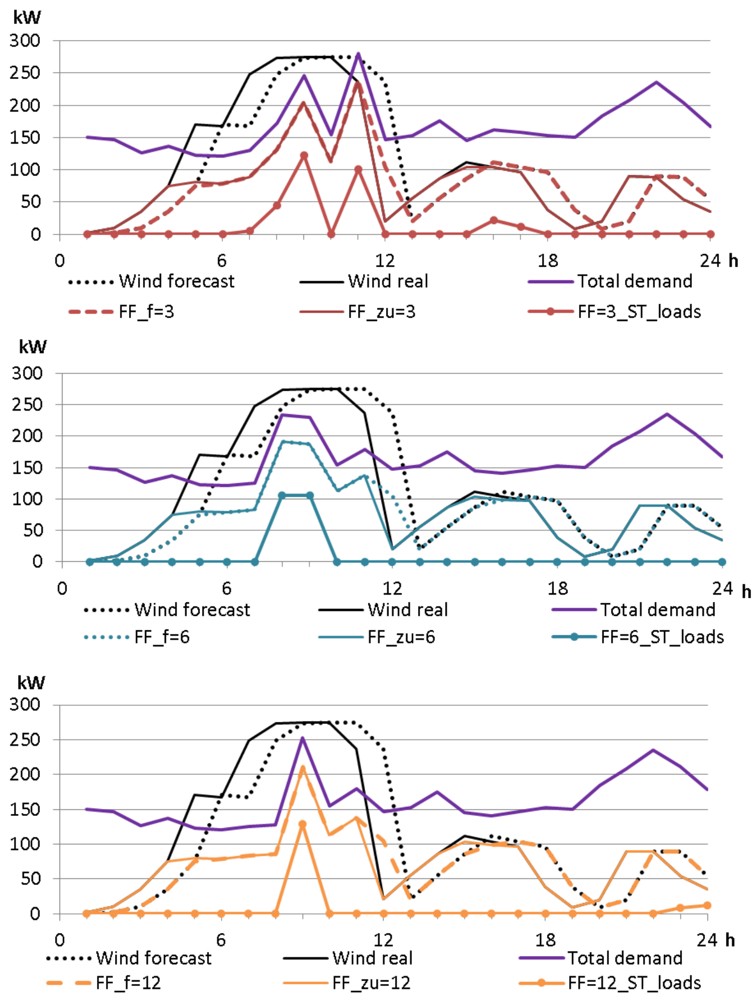

Figure VI.9 - Wind Power Available vs Wind Power Used and ST loads for DH/FH/FF=24/24/3-6-12

5.2 Three-day planning

In Table VI.8, a 3-day planning simulation was taken. Although the dispatch and generation costs of FF=3h and FF=12h are similar, the best result is achieved for the forecast frequency of 12h, because it is the one that best takes advantage of wind power, albeit being the model with larger backup done.

The impact of the forecast uncertainty on the dispatch costs regarding the zero-uncertainty model is 0.12%, 0.06% and -0.01% for model FF=3h, FF=6h and FF=12h, respectively, corresponding of 2.1%, 2.3% and 2.4% on average, of the daily load, which is considerably lower than those found for the day-ahead planning, showing that the impact of uncertainty for longer periods is dissipated, when ST backup needs decrease.

Table VI.8 - Comparison results for DH/FF/FF = 24/72/3-6-12

Population Size/Generations		10/20	
Dispatch horizon [h]		24	
Forecast horizon [h]		72	
Forecast frequency [h]	3	6	12
Maximum dispersion [%]	+0.9 %	+1.3 %	+1.3 %
Minimum fitness [€]	*2215.40*	1827.8	1592.90
Dispatch costs [€]	1579.40	*1587.1*	1579.40
Generation costs [€]	1429.40	*1437.1*	1429.40
Backup needs [kWh/3day]	329.90	329.90	329.90
Backup done [kWh/3day]	243.82	275.37	284.24
Unattended needs [kWh/3day]	*86.08*	54.53	45.66
Zero-uncertainty dispatch costs [€]	1577.50	*1586.2*	1579.50
Uncertainty impact on dispatch cost [€]	+0.12%	+0.06%	-0.01%

In terms of wind absorption, Table VI.9 and Figure VI.10 present the comparison of the forecast and zero-uncertainty models for the different FF indexes. While in Table VI.9 it is observed that the forecast model is overrated in the wind absorption, in plus 1.8% on average, in Figure VI.10 it is verified that ST loads continue to be placed when there is a surplus of wind energy.

Table VI.9 - Wind absorption for DH/FH/FF=24/72/3-6-12

	Wind absorption [%]		
Model	FF=3	FF=6	FF=12
Forecast	46.71%	46.49%	46.89%
Zero-uncertainty	44.98%	44.72%	45.07%

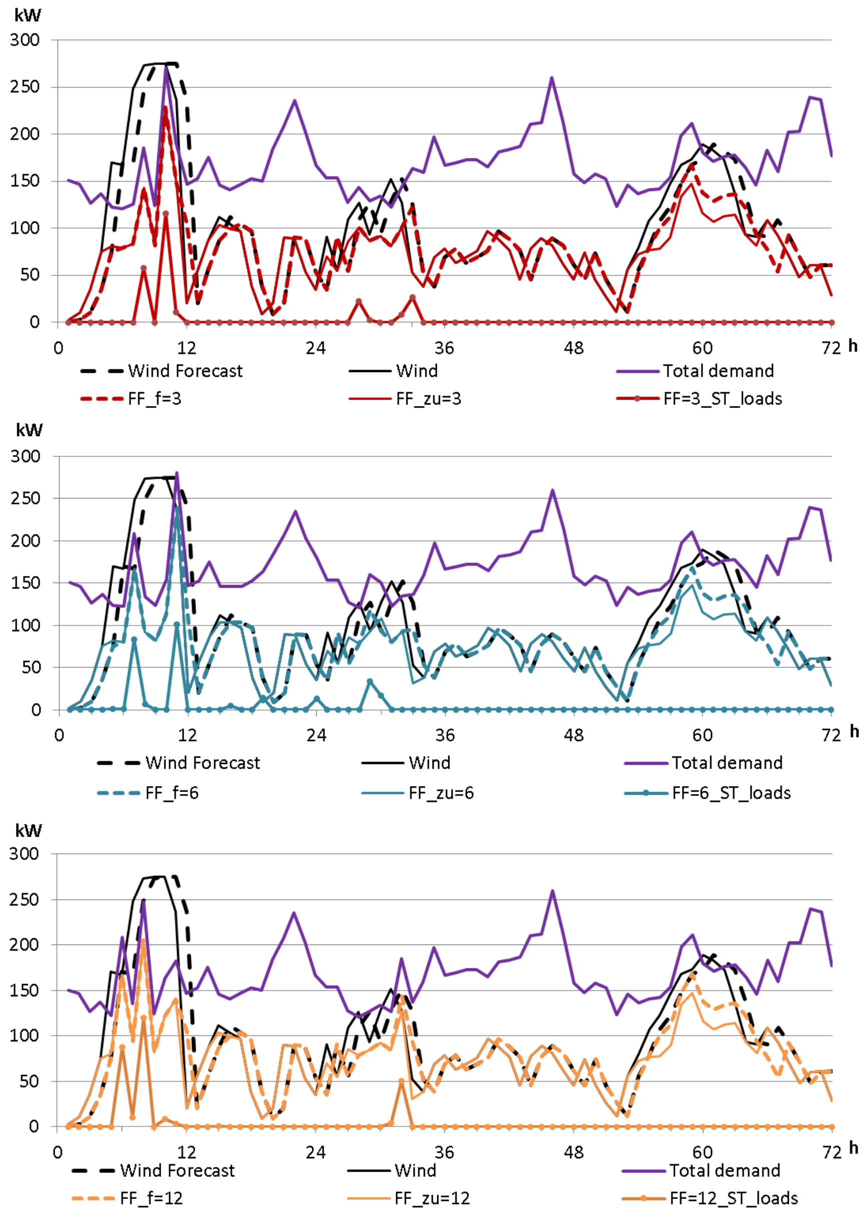

Figure VI.10 - Wind Power Available vs Wind Power Used and ST loads for DH/FH/FF=24/72/3-6-12

5.3 One-week planning

Table VI.10 presents the comparison of different dispatch horizons for a 7-day simulation (1 week). The table presents the results for a DH=24h and FF=6h, and additionally for the dispatch horizons of 24h, 48h and 72h with a forecast frequency of FF=12h.

Comparing the models DH=24h_FF=6h and DH=24h_FF=12h, the minimum fit is achieved with FF=12h, while the best dispatch and generation costs are achieved with FF=6h. This can be explained by the lower backup done in the model FF=6 which leads to lower generation costs, while model FF=12h seems to best harness the wind power since the zero-uncertainty costs are lower.

Looking at the comparison of the different dispatch horizons, the DH=72 h is the model with worst results, while DH=48 h seems best, albeit DH=24 h takes the minimum fit. The impact of the forecast uncertainties on the dispatch costs is, on average, -0.2%, for an average amount of flexible loads of 1.2% of daily demand. Looking at Table VI.11, DH=48 h takes the highest absorption of wind with 32.44% and 31.54% on the forecast and zero-uncertainty models, respectively, which is lower than the values found for FH of 24h and 72h. This can be explained by the major influence of wind forecast on the planning of the dispatch of flexible loads, which as seen above, are decreasing in this scenario. On average, per day, the difference between forecast and zero-uncertainty models of wind absorption is 0.96%.

Table VI.10 - Comparison results for DF/FH/FF= 24/168/6 and 24-48-72/168/12

Population Size/Generations	10/20		10/20	
Dispatch horizon [h]	24	24	48	72
Forecast horizon [h]	168		168	
Forecast frequency [h]	6		12	
Maximum dispersion [%]	+1.1 %	+0.2 %	+0.30%	-0.4%
Minimum fitness [€]	*6539.5*	4407.60	4565.40	*6146.8*
Dispatch costs [€]	4368.6	4370.20	4364.70	*4384.4*
Generation costs [€]	4088.6	4090.20	4084.70	*4104.4*
Backup needs [kWh/1week]	306.74	303.27	333.03	385.13
Backup done daily [kWh/1week]	334.09	340.73	339.68	261.31
Unattended needs [kWh/1week]	-27.35	-37.46	-6.65	*123.83*
Zero-uncertainty dispatch costs [€]	*4401.0*	4377.00	4372.30	*4396.8*
Uncertainty impact on dispatch cost [€]	-0.7%	-0.2%	-0.2%	-0.2%

Table VI.11 - Wind absorption for DH/FH/FF=24/168/6 and 24-48-72/168/12

	Wind absorption [%]			
Model	DH=24_FF=6	DH=24_FF=12	DH=48_FF=12	DH=72_FF=12
Forecast	32.35%	32.33%	32.44%	31.82%
Zero-uncertainty	31.32%	31.44%	31.54%	30.82%

Regarding the solar forecast uncertainty influence on dispatch, Figure VI.11 shows the balance of the thermal storage level and consequent availability of hot water backup needs, both real and forecast solar and wind power, and the total demand and DHW backup loads. It is observed that the uncertainty on solar forecast has a larger impact when the solar radiation and the thermal storage level are low, as exemplified by the first day. It is observed that, the thermal storage capacity is more relevant to the impact of solar forecast rather than the solar radiation. However, if the radiation is low for several days and the tank's storage levels go below the daily DHW needs, the uncertainty in the solar forecast becomes predominant, since it introduces backup needs that need to be accommodated.

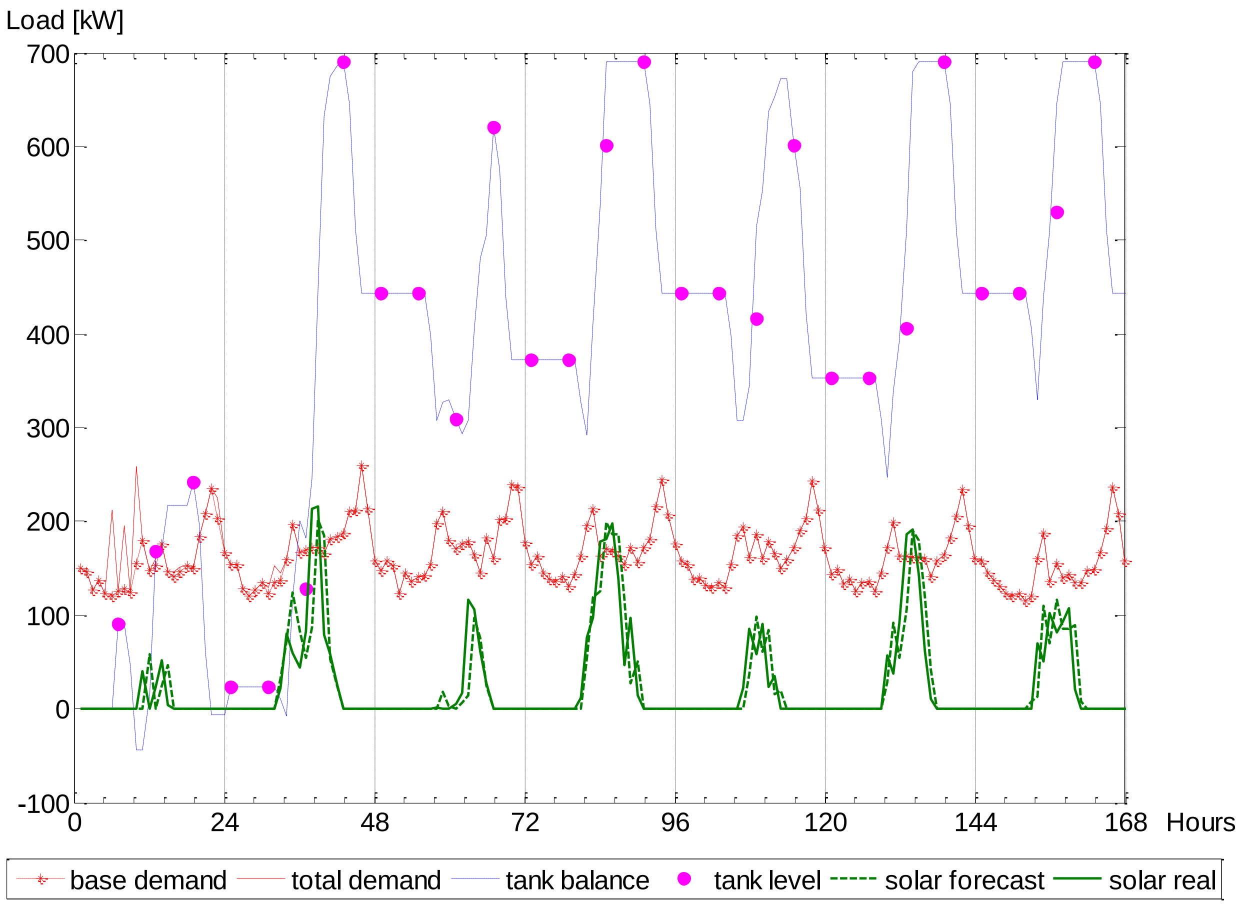

Figure VI.11 - One-week balance of thermal needs, level of storage, solar forecast and demand

6 Conclusions

This work explores the impact of forecast uncertainties on the performance of demand response of an isolated micro grid. Rather than focusing on which is the better forecast model for the system considered, the focus was to integrate uncertainties on the planning of the demand response. DHW backup needs are used as flexible load through a genetic algorithm optimization of the dispatch, maximizing wind penetration in the hybrid system.

The results show that the uncertainty of solar and wind forecasts has influence on the dispatch costs and management of flexible loads, although at different levels. The wind forecast is used to maximize the wind absorption through managing the flexible loads, although its uncertainty impact is dissipated with decreasing flexible loads. However the impact of the forecast uncertainty will depend on the forecast horizon taken into account, being lower for short term and higher for longer periods.

Regarding the solar forecast uncertainties, they are found to have less impact than the wind uncertainties, since they do not have an instantaneous impact in the grid. Nevertheless, since the backup loads of DHW systems are used in this study as flexible loads, the solar forecast uncertainties will present more impact when the thermal energy storage is below the daily DHW thermal demand. In other words, if a week of high solar radiation would be taken as example, the limitations of hot water tanks to act as a demand response agent would be more denotable.

Thinking on the possible application of this methodology to other hybrid renewable energy systems, some concerns must be consider: find the most suitable forecast method according to the weather regime and the type of final energy of the energy system in the considered location.

Although this study focused on assessing the impact of forecast uncertainties from the supply side in the demand response management, to consolidate this study, the uncertainties associated with the demand side should be embraced on further work.

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Chapter VII
Assessment of DHW systems' implementation with demand response capabilities on isolated microgrids, using a smart grid approach

Abstract

This work assesses the potential of demand response on isolated hybrid renewable energy systems, in order to optimize the systems' dispatch by minimizing the operation costs and the peak demand. The developed methodology models the implementation of solar thermal systems to replace non-renewable systems for the domestic hot water supply, and a demand response strategy to manage the backup loads required from the grid, in days of low solar radiation. This integrated energy methodology, previously developed and tested on the small and isolated island of Corvo, in Azores, is applied to other isolated microgrids with different scales and energy systems in order to identify the potential energy savings introduced by solar thermal systems with demand response capabilities.

The results show that larger savings are found for small islands, essentially with only residential loads and with renewable electricity generation capacity, as it enables the energy system to cope with the backup loads of the domestic hot water systems (DHW), without significant increases on the operation costs and tackling peak load increase. Regarding bigger islands, where the services and industry sectors dominate the load pattern, this implementation shows little technical and economic impact. In terms of environmental impact, this methodology shows that the combination of solar thermal systems with demand response programs may result in 88% less CO_2 emissions on average, than non-renewable DHW systems.

Keywords

Demand response; Smart grid; Isolated systems; Renewable energy; Thermal storage; Islands

1 Introduction

The energy systems of small isolated communities face great challenges regarding autonomy and grid resilience, when planning a sustainable energy future. The implementation of renewable energy technologies, either for electricity or heat supply, enables a growing security of supply for these isolated micro-communities as they require less fossil fuels for electricity and thermal generation, with diesel power plants becoming a reserve power for growing hybrid energy systems, while thermal demand can be assured by solar energy. Moreover, the potential to store or reschedule part of the electricity load on isolated energy systems, is seen as a promising opportunity to delay further investments on the power capacity of a grid.

A smart grid is one that incorporates information and communications' technology into every aspect of electricity generation, delivery and consumption, in order to minimize environmental impact, enhance markets, improve reliability and service, reduce costs and improve efficiency [1]. In this work, the smart grid approach includes the integration of renewables, storage and demand response technologies for a better grid performance. Hybridizing an energy system implies the integration of different energy technologies in order to raise security of supply, combining renewable and fossil energy sources. The impact of integrating storage systems, especially in isolated hybrid renewable energy systems (HRES), has been analyzed in different studies [2], with demand response (DR) being coupled with thermal systems as a way to manage peak load [3][4]. However, some technical operation challenges remain unsolved [5][6].

Many authors have tried different solutions of demand response following a smart grid approach either to increase renewable energy (RE) penetration, reduce peak load or decrease operations costs: in [7] a demand response strategy is enabled through signals to end-users for switching on and off the rice cookers, for improving the system reliability, with the decrease of peak-load; in [8] an optimal scheduling of household appliances is designed to reduce electricity operation costs; in [9], the use of demand side management for increasing renewable penetration is shown to delay the investment on further capacity of a microgrid.

In this paper, an integrated energy methodology, previously developed and tested on the small and isolated island of Corvo, in Azores, [10][11][12][13], is applied to other isolated islands with different scales and energy systems. In particular it analyzes the implementation of renewable thermal systems to replace non-renewable systems for Domestic Hot Water (DHW) supply, considering also the use of a demand response strategy to manage the additional backup loads required from the grid. In this case, solar thermal systems (ST) are implemented for DHW supply, thus replacing the imports of fuel. While the electric backup can cause a considerable increase on the peak load, it also presents an opportunity to implement a demand response strategy for improving the overall system operation, using the hot water tanks as "thermal batteries".

The results of the implementation of this strategy to Corvo Island were promising, but the potential for such an approach on different communities, with different social, economic, climatic conditions and different energy system configurations, remains to be analyzed. As found in [14], isolated HRES tend to have a pattern of design and implementation according to diverse community and energy system parameters such as location, number of population, demand per capita, type of energy demand and supply, annual demand and peak load, etc.

Overall, there is a knowledge gap on the economic, energy and environmental impact for different isolated hybrid renewable energy systems of the implementation of demand response capabilities on solar thermal systems as a way to increase energy efficiency while decreasing operation costs and managing peak increase. In particular, most studies use their own methodology and focus on only one energy system, making it impossible to compare findings across energy systems. Therefore, the main scientific contributions of this paper are:

- Comparison of the impact of introducing solar thermal systems with electric backup on different isolated energy systems;
- Assessment of the potential of using demand response of the DHW electric backups to reduce the operation costs of the associated electric systems;
- Estimation of CO_2 emissions reduction.

The paper is organized as follows: Section 2 describes the models and methodology used and how they were implemented, while in Section 3, the modeled islands are grouped and characterized; Section 4 presents the results and in Section 5 are referred the final statements of the work.

2 Methodology

2.1 Models description

In order to model and compare the influence of the implementation of ST with demand response actions between islands, it was necessary to implement two different models and do some general assumptions for each island.

2.1.4 DHW electric impact model

Equation VII.1 describes the solar gains from each ST system while the thermal demand of each house is calculated according to Equation VII.2. Both these inputs are necessary to determine the total electric backup needs. The model used is extensively described in [10].

$$Q_{solar}(\mathrm{t}) = \frac{A_{abs}}{1000}.(\mathrm{I_{col}}(t).\eta_{col}\text{-}(\frac{\mathrm{U_c}.(\mathrm{T_m}(t)\text{-}\mathrm{T_{amb}}(\mathrm{t}))+\varepsilon.\sigma.(\mathrm{T_m}(t)^4\text{-}\mathrm{T_{inlet}}(t)^4)}{8760}); \quad Q_{solar}(\mathrm{t})\geq 0 \;\; [\mathrm{kW}] \qquad \text{(VII.1)}$$

where:

- A_{abs} is the area of the flat-plate collector,
- $\mathrm{I_{col}}(t)$ is the hourly solar irradiation on the collector plane [W/m^2],
- η_{col} is the collector efficiency,
- $\mathrm{U_c}$ is the conductive loss' coefficient,
- ε is the emittance,
- σ is the Stefan-Boltzmann constant,
- $\mathrm{T_{amb}}(t)$ is the hourly ambient temperature,
- $\mathrm{T_{inlet}}(t)$ is the hourly inlet water temperature on collector and,
- $\mathrm{T_m}(t)$ is the hourly average temperature defined by $\mathrm{T_m}(t) = \frac{\mathrm{T}_{max}+\mathrm{T_{inlet}}(t)}{2}\ [K]$

$$\mathrm{Q}_{DHW}(t) = \frac{C_{p\ water} \cdot \rho_{water} \cdot V_{DHW}(t) \cdot (\mathrm{T_{max}} - \mathrm{T_{inlet}})}{1000.3600}\ [kW] \qquad \text{(VII.2)}$$

where:

- $C_{p\ water}$ is the specific water heat (4.186 KJ/kg.K);
- ρ_{water} is the water density (1000 kg/m^3);
- V_{DHW} is the volume, in liters, of hot water demand at each hour t.

For each island, a set of assumptions were made regarding the implementation of ST systems, which are listed in Table VII.1.

Table VII.1 - DHW modeling description

DHW modelling	
Number ST systems	• ST systems were considered to be implemented in 50% of the houses, to limit the impact on the peak load increase • The number of houses was found on statistical data or calculated considering an average occupancy of 3 person/dwelling; even if in some islands with lower Gross Domestic Product (GDP) per capita the reality can be different (with more people per house or lower DHW demand), this assumption was made in order to be able to compare the model between different types of islands
Characteristics of ST systems	• The ST systems were assumed to have optimal orientation and inclination for the location considered • Each ST system was dimensioned for 3 persons, with an area of 4 m^2, efficiency of 80% and using a hot water tank of 200 liters, just as describe in [10]
DHW demand profile	• Three equally distributed groups of DHW profiles were considered, just as described in [10], totaling a consumption per house of 6.28 kWh_t /day (120 l): ○ Morning consumers (mainly morning demand); ○ Evening consumers (mainly evening demand); ○ Distributed consumers (where the thermal demand is distributed throughout morning, midday and evening).

2.1.5 Economic dispatch model

Regarding the economic dispatch model, Figure VII.1 presents in detail how the model works, while Table VII.2 describes how the model was adapted for the specification of each island. The model used is further described in [11].

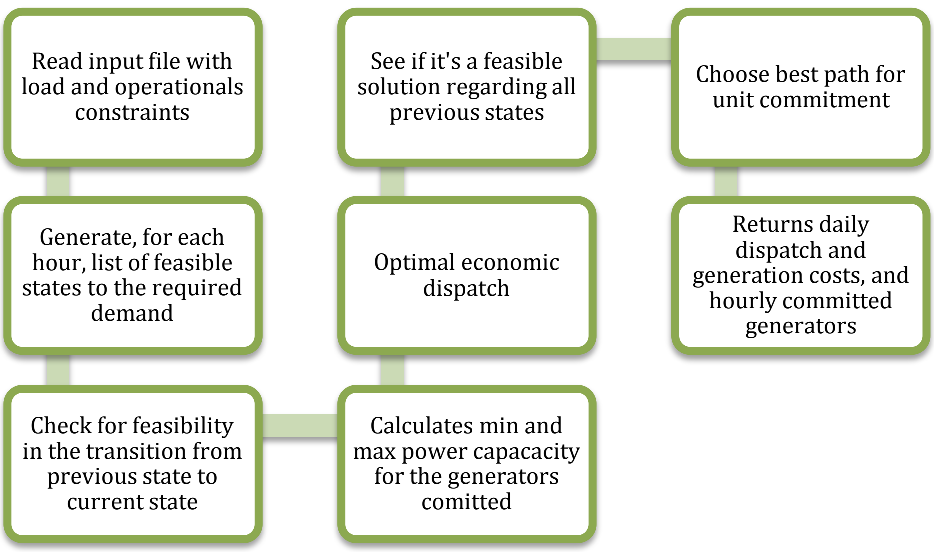

Figure VII.1 - Economic dispatch model algorithm description

Table VII.2 - Economic Dispatch description

Economic dispatch modeling	
Diesel generators	• When in presence of the nominal capacity of each generator, they were modeled accordingly • In the absence of information, generators were assumed to be a multiple of total nominal capacity, of standard capacity available in the market • The diesel price for each location was considered • For dispatch costs account, various operation constraints as minimum up/down times, ramp up/down times and start-up/shut-down costs were considered
Wind generators	• When in presence of wind capacity, wind turbines were modeled accordingly with the specifications and power curves given by the manufacturer, being dispatched in groups of turbines, with the same nominal capacity • No costs were associated with wind generation and full priority in dispatch was given
PV plant	• When in presence of photovoltaic (PV) plants, the systems were modeled with 18% efficiency, and dispatched as a single generator • No costs were associated with solar generation and full priority in dispatch was given

The renewable resources data for each location (solar and wind resources), was obtained from NASA [21] for the capital of each island. Regarding solar data, hourly solar irradiation on the optimal plane (oriented South or North, in case of being located on the northern or southern hemisphere, respectively) for one year, based on 22-year average, was obtained and introduced on the ST systems' calculations. For the case studies with wind energy installed, hourly wind speed was estimated for a height of 50 m through monthly distribution data and according with the daily averages of each month.

Demand response is assumed to be centrally managed by the utility, providing the flexibility to use the electric backup loads from DHW systems to optimize the loads dispatch, in order to minimize the operation costs and the peak increase of each studied island. With that in mind, a genetic algorithms optimization to the placement of the DHW flexible loads was developed and chosen among others optimization techniques [11][12], since it has demonstrated suitability and the best performance for this problem formulation. For further detail, this approach is exhaustively described in [11].

2.2 Methodology implementation

Figure VII.2 presents how the methodology can be implemented to different islands in order to assess the potential of DHW electric backup as flexible load on isolated HRES. First, each island needs to be characterized in terms of the average daily hourly load, the annual peak demand, the energy systems specifications (capacities, efficiencies, and other relevant data), renewable energy resources, number of houses and average persons/house and DHW demand profile. Then, the DHW electric impact model is applied to estimate the load increase on the grid, after which the economic dispatch model is applied for an average day. Afterwards, genetic algorithms are used to optimize the demand response using the DHW backup loads. Finally, the results are compared in terms of the dispatch/generation costs, peak demand reduction and CO_2 emissions.

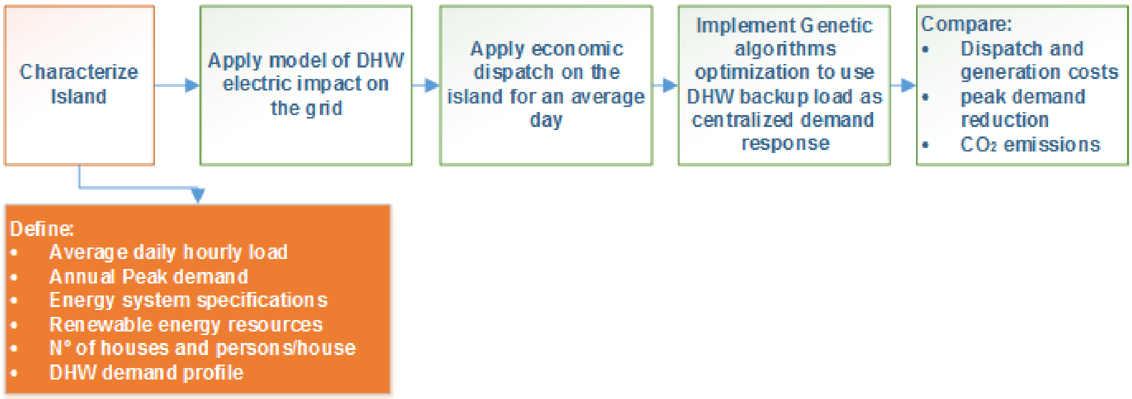

Figure VII.2 - Methodology description

The methodology considers three scenarios with different characteristics, and was implemented for an average day for each island. The three scenarios are:

- *Base load scenario* – the average daily load of the considered island was modeled through the economic dispatch model described in [11]: this model is a daily economic dispatch model that combines the unit commitment problem and a linear dispatch method, taking into account operational restrictions of various types for the generating technologies, such as start-up/shut-down costs, minimum up/down time, ramp up/down rate, minimum power output and operating reserve. The model works with an hourly time-step, calculating for each hour the generation and dispatch costs;

- *DHW at demand scenario* – the hourly average DHW electric demand was added to the base load (at the hour that the hot water is consumed, as described in [10]), and the island's economic dispatch was modeled according to [11];

- *DHW demand response scenario* – the daily average DHW backup average was added hourly to the base load, using the genetic algorithm optimization method described in [11], and the economic dispatch was modeled using the same methodology as in the other scenarios.

The results between dispatch scenarios were compared for the different islands.

3 Case studies' characterization

Isolated HRES are characterized by different parameters such as location, number of population, demand per capita, type of energy demand and supply (dependent on the economic structure), annual demand and peak load [14]. Different locations on the globe have an impact on the demand per capita, and have also different solar resource availability. Thus, the systems will have different amounts of ST backup flexible loads to be managed. The population is directly related with the energy demand, and the type of demand pattern gives an estimation of the peak load per capita, and consequently the installed power capacity. Demand needs (annual and peak load) are also related with the type of energy system supply: the need to respond to the seasonality of demand (in case of tourism) leads to an oversized energy system beyond the population needs, using frequently renewables to match that need. However, in presence of renewables, the power capacity has to be larger since they are intermittent, not assuring continuous supply.

Table VII.3 shows a summary of the most relevant characteristics considered in this work. Each case study designation corresponds to an island that is further specified and studied.

Table VII.3 - Summary of different parameters considered for different case studies

Group designation	**Case study designation**	**Hemisphere Location**	**Population**	**Power installed**	**Energy system**	**Demand pattern**
A	A1	North	< 1000	< 1 MW	Fossil fuels	Residential
	A2	South				
B	B1	North	< 2000	< 10 MW	Fossil fuels+ RE	Residential + Tourism
	B2	South				
C	C1	North	< 10 000	< 20 MW	Fossil fuels	Residential + Services + Tourism
	C2	South				
	C3	North			Fossil fuels + RE	
	C4	South				
D	D1	North	< 100 000	< 100 MW	Fossil fuels + RE	Residential + Industry + Services + Tourism
	D2	South				

The case studies adopted for this work that are representative of the diverse characteristics presented in Table VII.3, are presented in detail in Table VII.4 based on the data collected for 10 different islands around the world. On the types of energy supply, *DPP* refers to Diesel Power Plant, *Wind* to wind power plant and *PV* to the existence of a photovoltaic power plant. It is relevant to denote that information on DHW supply is hard to find in most cases for these isolated systems, since there is no centralized supply of heat, so the DHW demand was estimated using reference values for residential demand [15].

The load patterns were found through literature review, except for the cases of King Island, in Tasmania, Sal Island, in Cape Verde and Mahé Island, in Seychelles. In these cases, an adaptation of the daily load profile of similar islands was used, through the normalization of the total average daily demand of each island. For King Island, the load pattern of the main island of Tasmania was used as reference. For Sal and Mahé, the island of Crete, in Greece, was used as they have the same type of demand pattern (residential, tourism and industry), despite the different economic environment and development level. In Figure VII.3, the daily load patterns of the different islands are compared and grouped as defined in Table VII.4.

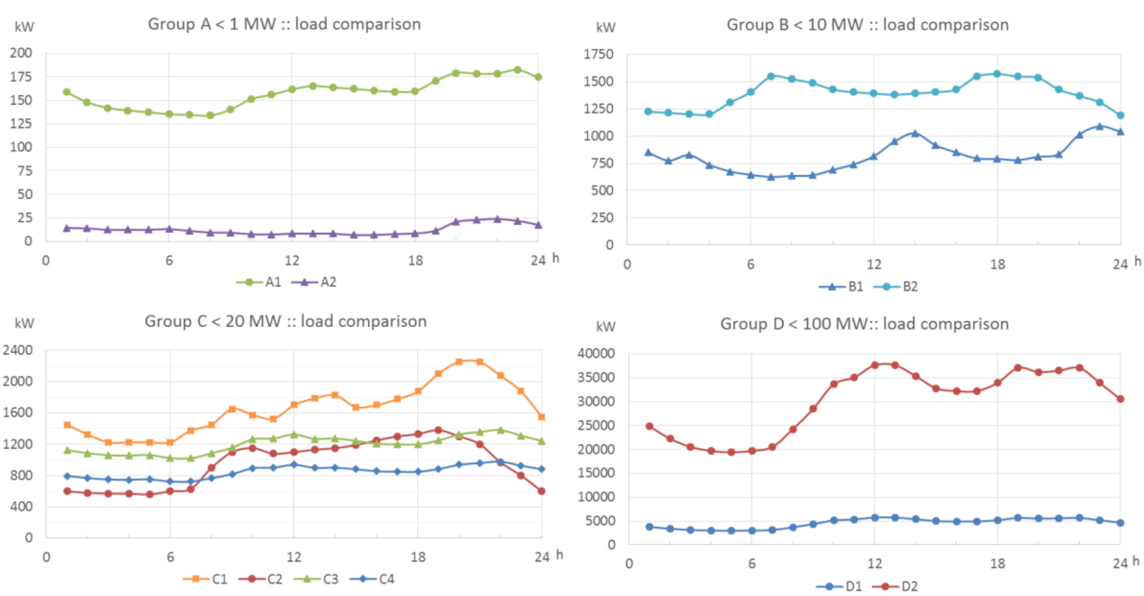

Figure VII.3 - Load comparison between groups of islands

Group A compares islands with less than 1000 inhabitants and less than 1 MW power installed. It is seen that Corvo (A1) has a residential demand pattern, with European energy demand standards, while Nolhivaranfaru (A2) has a very low load pattern, which represents mostly lighting needs, after sunset, from the residential sector - also the low GDP per capita and an annual 0.17 MWh demand per capita, indicates that the access to electricity is very limited.

Table VII.4 - Island parameters description

	Island	Population	GDP per capita[2]	Type of energy system	RE	Power Installed	Annual Demand	Peak load	Annual Demand per capita	Average Daily Demand	Type of DHW supply	Diesel Price	References
		[nr]	[int$/cap]		[%]	[MW]	[GWh]	[MW]	[MWh/cap]	[MWh/day]		[€/l]	
A1	Corvo, Azores, Portugal	430	22.9	DPP	-	0.54	1.4	0.255	3.26	4.03	LPG[3] (converted to ST and HP)	0.69	[10][16]
A2	Nolhivaranfaru, Maldives	650	9.1	DPP	-	0.06	0.1	0.038	0.17	0.30	n/a	0.33	[17][18]
B1	Kythnos, Greece	1456	23.6	DPP + Wind + PV	33%	2.80	5.6	1.61	3.87	15.42	30% ST	0.80	[19][20]
B2	King Island, Tasmania	1800	43	DPP + Wind + PV	65%	8.55	12.2	3.30	6.77	33.41	n/a	1.08	[21][22][23]
C1	Salina, Sicily, Italy	4000	29.6	DPP	-	3.70	15.2	3.60	3.80	41.62	n/a	0.80	[24][25]
C2	Norfolk Island, Australia	2302	43	DPP	-	6.00	7.9	1.60	3.43	21.64	LPG	0.48	[26][27][28]
C3	Flores, Azores, Portugal	3791	22.9	DPP+ Wind	11%	4.30	10.2	2.04	2.68	27.83	n/a	0.65	[16]
C4	Saint Helena	4225	7.8	DPP + Wind + PV	25%	8.60	7.4	n/a	1.76	20.38	25% ST	0.61	[29][30]
D1	Sal, Cape Verde	20702	4.4	DPP+ Wind + PV	35%	36.80	40.1	8.39	1.93	109.74	n/a	0.57	[31][32][33]
D2	Mahé, Seychelles	78539	25	DPP+ Wind	2%	64.00	305	38.0	3.88	835.62	n/a	0.84	[34][35]

[2] GDP - per capita (PPP), *The World Factbook*, Central Intelligence Agency. *Last accessed in April 2015*

[3] LPG – Liquefied Petroleum Gas

In Group B, islands with less than 2000 inhabitants and less than 10 MW power installed are compared. The island of Kythnos (B1) is dominated by tourism and residential loads, which leads to midday and evening peaks, while King Island (B2) has a base load considerably higher (business related) and with morning and evening peaks, influenced highly by the residential sector.

Group C consists of islands with less than 10 000 inhabitants and less than 20 MW power installed. While Salina (C1) and Norfolk (C2) have denotable peaks from tourism, with Salina having a much higher base load, Flores (C3) and Saint Helena (C4) have mostly a smooth residential profile.

Finally, Group D consists of the bigger islands, with less than 100 000 inhabitants and a power capacity of less than 100 MW. While Sal (D1) has a smoother profile, with a significant influence of the residential and tourism sectors, Mahé (D2) is mostly influenced by the canning industry and tourism, also having a higher base load since it has 3 times more population than Sal Island.

4 Results and discussion

4.1 Scenarios comparison

Table VII.5 presents the results comparison for the different case-studies, showing the absolute values for the daily dispatch costs and peak load, presenting also the variations of each to the base load scenario on relative percentages, on purple and green shades, respectively. Figure VII.4, Figure VII.5, Figure VII.6 and Figure VII.7 show graphically the load for the different scenarios, for each group of islands, presenting for the islands with renewable resources, the wind power available (*Wind*) and the photovoltaic power available (*PV*), calculated according to the renewable resource and system installed.

Looking into Group A in detail, it is possible to observe that in the *DHW at demand* scenario there is an increase on the daily dispatch costs. While for the case study A2, this increase is very significant, reaching 11.3% (for a 13.0% increase on peak load), for the case study A1 it is just 1.0% (for a 4.5% increase on peak demand). As can be seen in Figure VII.4, the *DHW at demand* scenario increases considerably the evening peak load, while the *DHW demand response* scenario tries to distribute the additional load along the hours, to take advantage of the committed generators, leading to a peak load reduction to the values previously found on *base load* scenario (0% increase), albeit having a residual decrease of dispatch costs, of 0.1% and 0.01% for the case studies A1 and A2, respectively.

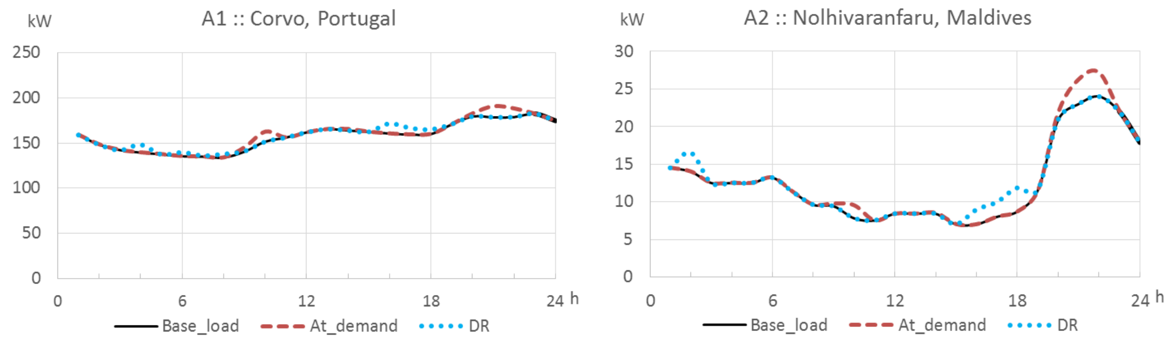

Figure VII.4 - Group A load scenario comparison

Observing Group B, the increase in dispatch costs is around 0.8%, being lower than for group A for the *DHW at demand* scenario, which can be explained by the presence of renewable generation, and 0% increase on peak demand, as can be seen in Figure VII.5. This shows us that the biggest responsible for peak load in the island is not the residential sector. For the *DHW demand response* scenario, the peak load also remains unchanged, while for B1 the dispatch costs are around the same of *DHW at demand* scenario (0% savings) and B2 records 0.8% savings, returning to the values found for *base load* scenario, which can mean that RE is already supplying most of the generation, especially on the B2 case.

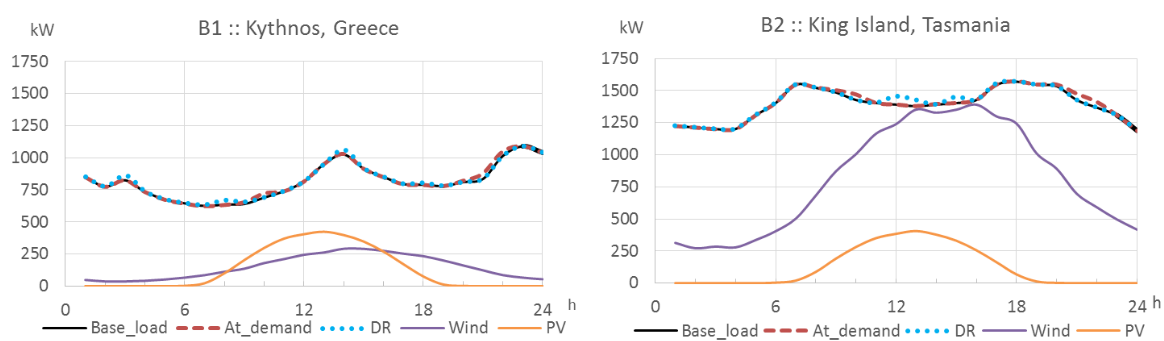

Figure VII.5 - Group B load scenario comparison

Table VII.5 - Results comparison

	Island	Houses with ST	Base load		DHW at demand						DHW demand response					Worst case annual peak
			Dispatch costs	Peak load	Dispatch costs	Δ costs	Peak load	Δ peak	DHW backup daily demand	DHW backup % daily demand	Dispatch costs	Δ costs	Peak load	Δ peak	DHW load	
		[nr]	[€/d]	[kW]	[€/d]	[%]	[kW]	[%]	[kWh/d]	[%/d]	[€/d]	[%]	[kW]	[%]	[kWh]	[kW]
A1	Corvo, Azores, Portugal	66	803	182	812	1.03%	191	4.54%	42.4	1.12%	811	0.93%	182	0.00%	42.3	390
A2	Nolhivaranfaru, Maldives	50	35	24	39	11.27%	27	13.04%	9.6	3.09%	39	11.26%	24	0.00%	9.5	143
B1	Kythnos, Greece	243	3 142	1 090	3 168	0.81%	1 090	0.00%	140.1	0.71%	3 168	0.81%	1 090	0.00%	140.3	2 114
B2	King Island, Tasmania	300	3 931	1 569	3 962	0.80%	1 569	0.00%	163.5	0.49%	3 931	0.00%	1 569	0.00%	165.6	3 928
C1	Salina, Sicily, Italy	954	7 898	2 250	8 017	1.52%	2 430	8.00%	584.0	1.45%	8 008	1.39%	2 250	0.00%	599.7	5 597
C2	Norfolk Island, Australia	508	3 506	1 380	3 547	1.16%	1 380	0.00%	310.3	1.35%	3 547	1.15%	1 380	0.00%	307.1	2 661
C3	Flores, Azores, Portugal	499	3 349	1 382	3 421	2.14%	1 470	6.39%	379.1	1.30%	3 399	1.48%	1 382	0.00%	379.2	3 087
C4	Saint Helena	799	2 559	978	2 593	1.34%	1 040	6.30%	226.4	1.10%	2 593	1.34%	978	0.00%	226.4	5 972
D1	Sal, Cape Verde	2070	4 255	5 726	4 261	0.14%	5 726	0.00%	65.0	0.06%	4 255	0.00%	5 726	0.00%	63.5	10 806
D2	Mahé, Seychelles	9500	177 210	43 597	177 780	0.32%	43 698	0.23%	2 722.2	0.32%	177 780	0.32%	43 597	0.00%	2 723.4	57 632

Regarding Group C (Figure VII.6), for the *DHW at demand* scenario, the increase on dispatch costs is between [1.2-2.1%], with C3 having the largest increase (2.1%), corresponding to a 6.4% increase on peak load. This is probably due to the fact that RE generation accounts for only 11% of electricity generation, while for C4 it accounts for 25% RE generation. Despite having almost the same peak load increase (6.3%) the impact on the dispatch costs is lower for the case study C4 (1.34%). The biggest peak load increase (8%) is found for C1, while for C2 it is null. This can be explained by the increase on the evening peak (C1 still has a load pattern with great influence of residential sector). Observing the *DHW demand response* scenario, all islands achieve a reduction on peak load, having savings on the dispatch cost, comparing with the *DHW at demand* scenario, between [0.00-0.66%]. These are more relevant on C3 (where the presence of RE generation is small, around 11%) and on C1 (all fuel-powered), which is coherent, since the main driver for the increase on dispatch costs are the diesel consuming generators during peak hours. On the other hand, for C2 and C4 the cost savings are almost null. For C2, this can be explained by the fact that the peak load remains unchanged compared to the *base load* scenario, and for C4, by the additional load being absorbed by the moderate renewable generation (25%).

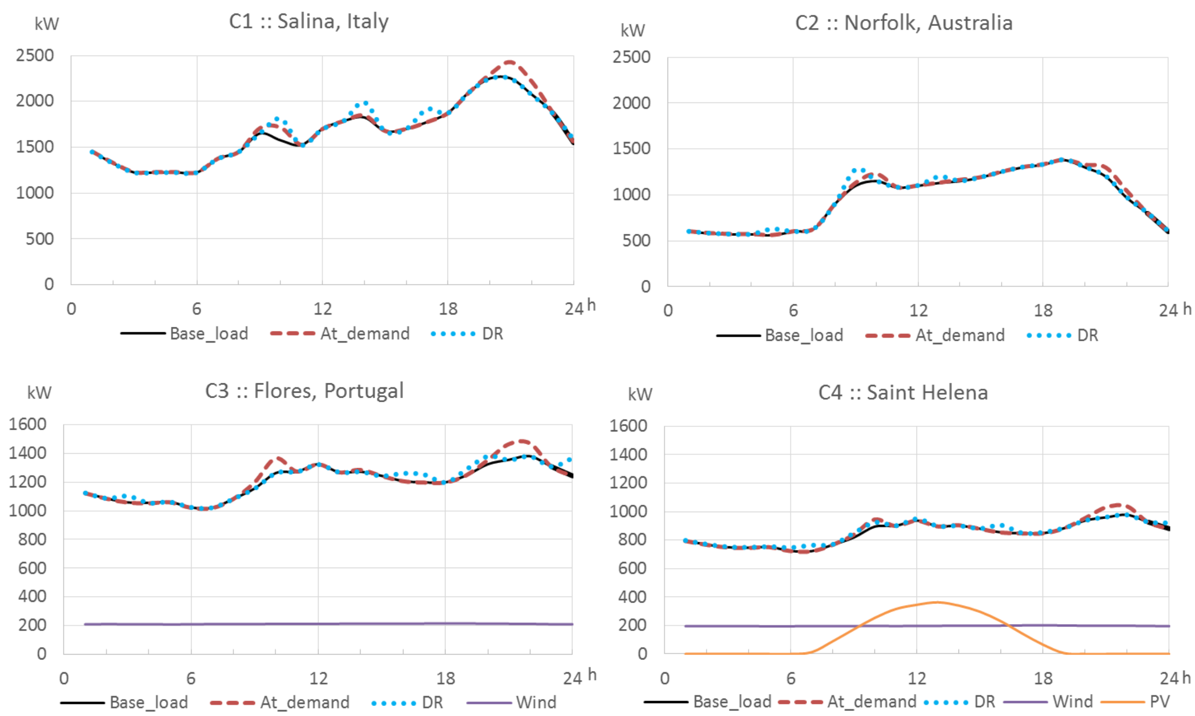

Figure VII.6 - Group C load scenario comparison

Looking in detail at group D, the increase in dispatch costs and peak demand for the *DHW at demand* scenario is residual, of [0.1-0.3%] and [0.0 -0.2%] respectively, as can be seen on Figure VII.7. For the *DHW demand response* scenario, the peak load increase is null (same value of *base load* scenario), while in terms of dispatch costs, D1 presents 0.1% savings and D2 does not show any changes compared to the *DHW at demand* scenario.

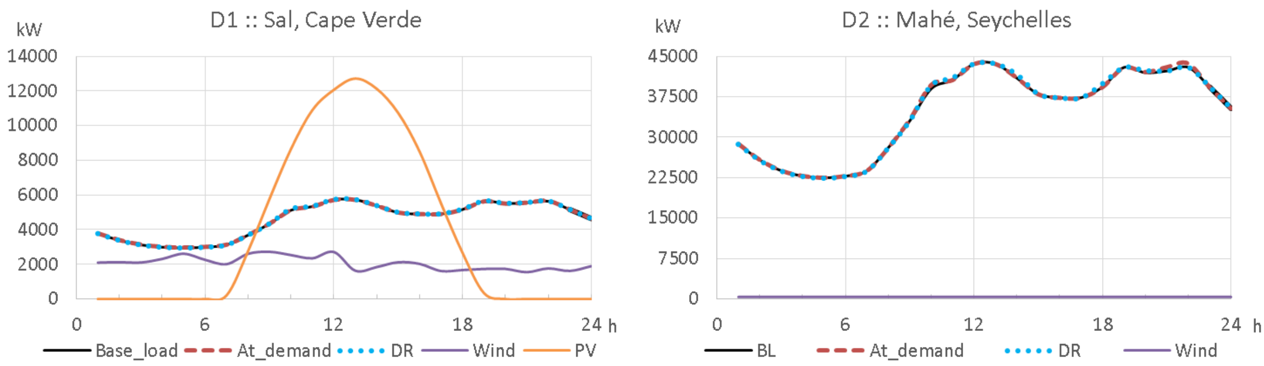

Figure VII.7 - Group D load scenario comparison

In conclusion, regarding the implementation of ST systems, impacts of [0.1-3.1%] on the daily electricity demand were estimated. This influence is higher on the islands where the load pattern is essentially residential and the demand per capita is low as is the case of A2 (3.1% daily demand). However, for group C, whose islands are a mix of residential with tourism and services, the ST impact is on average 1.3% of the daily load. Regarding the bigger islands, the impact is residual (0.1% to 0.3%) due to the load patterns being essentially from tourism and services, and having also abundant solar irradiation which decreases the electricity needs.

In general for the *DHW at demand* scenario, it is seen that the impact in the costs ranges from [0.1-2.1%], except for the A2 case where an impact of 11.3% is shown, and is greater on systems without renewable generation, since they represent directly an increase on the fuel costs. There is also a direct impact on the increase of peak load, from [0.0-8.0%], except for A2 where the impact is 13%. The results found for the A2 case are an exception for the rest of the cases, due to the limited existent electric system (two diesel generators with a total capacity of 61 kW) dimensioned with little flexibility to support an increase of the existent peak load (38 kW), since the load pattern is itself very low (dominated the lighting need at night).

Regarding the *DHW demand response* scenario, it is possible to observe that the main benefits introduced by the flexible loads are the decrease in peak load, which achieves 0% increase compared to *base load* values for all cases, while dispatch costs are very similar to the ones found for *DHW at demand* scenario (maximum 0.8% variation).

In general the savings seem to be low, but that can be explained by the fact that average loads are being considered, instead of worst case days. Nevertheless, the approach of average day was chosen, since for savings analysis, it is the closest to reality on an annual balance. Nonetheless, to check if the actual electricity system is able to respond to the maximum peak demand of ST load, the worst case annual peak is presented, which represents the sum of the island peak load reported in Table VII.4, with the maximum annual peak load of ST systems, calculated through the DHW electric impact model. As can be seen in Table VII.5, by the values shaded in grey, there are two cases, A2 and C1, where the installed capacity may not support the peak increase. For the case study A2, which is the island with the lowest demand per capita, the electricity system is not dimensioned for massive implementation of residential electric appliances. For the case study C1, that can be explained by the island having a considerably high annual demand (15 GWh) and peak load (3.6 MW) for the installed capacity (3.7 MW), leaving small room for demand growth rate on the residential sector.

4.2 Investment costs for the implementation of ST with DR actions

Table VII.6 presents the increase on operation costs from the implementation of ST systems, with and without DR capabilities. For islands that have already an electricity generation partly based on renewables, the increase in operation costs is not significant, like the B2 or D1 cases, with 65% and 35% RE generation, respectively. However, for islands as C1 and D2, with moderate electricity demand and an exclusive or predominantly fuel powered electricity system, the increase in operation costs due to the electric backups of the ST systems becomes more dependent on the cost of the non-renewable energy sources used.

The difference between the two operation costs establishes a limit for the cost of implementing the DR system based on the electric backup of the DHW system. As can be seen from Table VII.6, these values range from 0 to 11.5 k€/year, on island's total values, but if these values are divided by the number of houses with ST implementation with DR of each island, the limits for investing in this technology would range from 0 to 38 €/year, with an average of 6.4 €/year. These are modest savings, but if we internalize the environmental costs of CO_2 emissions of the conventional systems (Liquefied Petroleum Gas (LPG) and electric boilers), the ST+DR solution could gain ground as a sustainable solution, as will be shown on Table VII.7.

Table VII.6 - Scenarios increase on investment costs

	Island	**Increase on the operation costs of the island** **DHW at demand** [k€/year]	**DHW Demand response** [k€/year]	**Δ costs** [€/year]	**DR cost per house with ST** [€/year]
A1	Corvo, Azores, Portugal	3.01	2.74	270	4.1
A2	Nolhivaranfaru, Maldives	1.45	1.44	10	0.2
B1	Kythnos, Greece	9.34	9.34	0	0.0
B2	King Island, Tasmania	11.50	0.00	11 498	38.3
C1	Salina, Sicily, Italy	43.73	40.11	3 613	3.8
C2	Norfolk Island, Australia	14.82	14.67	146	0.3
C3	Flores, Azores, Portugal	26.17	18.10	8 066	16.2
C4	Saint Helena	12.52	12.52	0	0.00
D1	Sal, Cape Verde	2.19	0.00	2 190	1.1
D2	Mahé, Seychelles	208.05	208.05	0	0.0

4.3 CO_2 emissions comparison of different DHW configurations

In Table VII.7, the CO_2 emissions of the islands' base load (without the inputted ST emissions) are shown, together with scenarios of possible configurations of DHW supply: solar thermal systems with no demand response (*ST at demand*), solar thermal systems with demand response capabilities (*ST+DR*), LPG boilers and electric boilers.

For the *ST at demand* and *ST+DR* scenarios the results are calculated considering the increase on generation costs from *base load* scenario to *DHW at demand* and *DHW demand response* scenarios, respectively - converting to liters of consumed diesel - diesel price is different for each island, as stated in Table VII.4 - and assuming a coefficient of emission of 2.68 kg CO_2/l $_{diesel}$. For the LPG burners scenario, an efficiency of 70% was considered, using an energy content of 12.73 kWh/kg $_{LPG}$ and a coefficient of CO_2 emission of 3 kg CO_2/kg $_{LPG}$, while for the electric heaters an efficiency of 80% was considered, using diesel as electricity supplier with an energy content of 11.92 kWh/kg $_{diesel}$ and a coefficient of CO_2 emission of 3.2 kg CO_2/kg $_{diesel}$.

The *ST+DR* scenario is the one that presents lower CO_2 emissions, with an increase compared to *base load* scenario between 0% (in cases where the dispatch costs remained unchanged, like B2 and D1) and 2.8% (for A2), with the average being around 1%. This scenario presents on average less 88% emissions than the non-renewable solutions (LPG and electric boilers).

Table VII.7 - CO_2 emissions

	Island	***Estimated base load CO_2 emissions (without ST)*** [ton CO_2/year]	***DHW CO_2 emissions comparison*** [ton CO_2/year]			
			ST at demand	**ST+DR**	**LPG**	**Electric boilers**
A1	Corvo, Azores, Portugal	1 133	11.6	10.6 (0.9%)	50.9	50.8
A2	Nolhivaranfaru, Maldives	104	2.9	2.9 (2.8%)	38.6	38.5
B1	Kythnos, Greece	3 769	31.3	31.3 (0.8%)	187.2	186.6
B2	King Island, Tasmania	3 515	28.5	0.00 (0%)	231.5	230.7
C1	Salina, Sicily, Italy	9 583	135.0	134.4 (1.4%)	736.1	733.7
C2	Norfolk Island, Australia	7 023	82.0	81.2 (1.2%)	392.3	391.1
C3	Flores, Azores, Portugal	4 989	107.7	74.5 (1.5%)	385.0	383.8
C4	Saint Helena	4 098	54.9	54.9 (1.3%)	616.5	614.5
D1	Sal, Cape Verde	7 149	10.2	0.00 (0%)	1 597.3	1 592.1
D2	Mahé, Seychelles	205 283	660.6	660.6 (0.3%)	7 330.0	7 306.2

5 Conclusions

A methodology for modeling demand response for the optimization of the economic dispatch of electric backup of solar thermal systems is tested here for different configurations of isolated microgrids of hybrid renewable energy systems. The methodology shows that the implementation of ST systems for DHW supply can represent an increase of 0.1% to 3% of the daily average demand, when looking at bigger or small islands, respectively.

The introduction of demand response capabilities for controlling the electric backups in small islands (with an electric installed capacity under 20 MW) can have significant advantages in peak load control - and consequently on the need to invest in additional power generation capacity - and CO_2 emissions reduction, especially if they present a HRES with a share of renewable generation larger than 25%. While for *DHW at demand* the additional loads from the DHW implementation increase considerably the peak load, the *DHW demand response* scenario shows that demand response can help the system to better manage the load increases, leaving the peak load unchanged.

However, very small islands with fuel-powered electric systems dimensioned for very low intensity demand patterns might not have the flexibility to cope with the increase on the dispatch costs and peak demand of the implementation of such appliances. Regarding bigger islands (with power installed from 20 to 100 MW), where the services and industry sectors dominate the load pattern, the use of demand response strategies to manage DHW backup demonstrates to have little economic and peak load impacts. In terms of CO_2 emissions, ST systems with DR capabilities can result in 88% fewer emissions than other fuel-powered DHW powered solutions.

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